

Research Report

Synthesis of a Naphthodiazaborinine and Its Verification by Planarization with Atomic Force Microscopy

Zsolt Majzik¹, Ana B. Cuenca², Niko Pavliček¹, Núria Miralles², Gerhard Meyer¹, Leo Gross¹, and Elena Fernández²

¹IBM Research – Zurich, 8803 Rüschlikon, Switzerland

²Department Química Física i Inorgànica, University Rovira i Virgili, 43007 Tarragona, Spain

This document is the Accepted Manuscript version of a Published Work that appeared in final form in *ACS Nano* **10**(5), pp 5340–5345 (April 25, 2016) copyright © American Chemical Society after peer review and technical editing by the publisher.

To access the final edited and published work, see

<http://pubs.acs.org/doi/abs/10.1021/acsnano.6b01484>

LIMITED DISTRIBUTION NOTICE

This report has been submitted for publication outside of IBM and will probably be copyrighted if accepted for publication. It has been issued as a Research Report for early dissemination of its contents. In view of the transfer of copyright to the outside publisher, its distribution outside of IBM prior to publication should be limited to peer communications and specific requests. After outside publication, requests should be filled only by reprints or legally obtained copies (e.g., payment of royalties). Some reports are available at <http://domino.watson.ibm.com/library/Cyberdig.nsf/home>.



Research

Almaden – Austin – Beijing – Brazil – Cambridge – Dublin – Haifa – India – Kenya – Melbourne – T.J. Watson – Tokyo – Zurich

Synthesis of a naphthodiazaborinine and its verification by planarization with AFM

Zsolt Majzik,^{*,†,¶} Ana B. Cuenca,^{‡,¶} Niko Pavliček,[†] Núria Miralles,[‡] Gerhard Meyer,[†] Leo Gross,[†] and Elena Fernández^{*,‡}

[†]*IBM Research - Zurich, 8803 Rüschlikon, Switzerland*

[‡]*Department Física Química i Inorgànica, University Rovira i Virgili, 43007 Tarragona Spain*

[¶]*Both authors have contributed equally to this project*

E-mail: zsolt.majzik@gmail.com; mariaelena.fernandez@urv.cat

Abstract

Aiming to study new motifs, potentially active as functional materials, we performed the synthesis of a naphthodiazaborinine (the BN isoster of the phenalenyl anion) that is bonded to a hindered di-ortho substituted aryl system (9-anthracene). We used atomic force microscopy (AFM) and succeed in both, the verification of the original non-planar structure of the molecule and the planarization of the skeleton by removing H atoms that cause steric hindrance. This study demonstrated that planarization by atomic manipulation is a possible route for extending molecular identification by AFM to nonplanar molecular systems that are difficult to be probed with AFM directly.

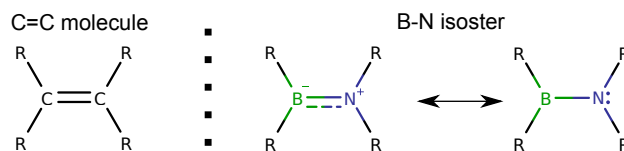
Abbreviations

AFM = Atomic Force Microscopy, STM = Scanning Tunneling Microscopy, DFT = Density Functional Theory, Bdan = Boron(1,8)diaminonaphthalene

Keywords

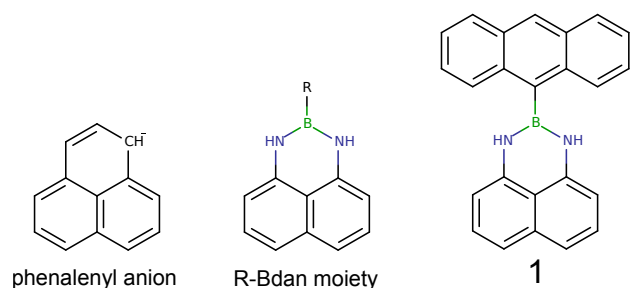
Bdan, AFM, STM, dehydrogenation, radical, steric hindrance

The boron-nitrogen substitution of two adjacent carbon atoms in a C=C bond, referred to as BN/CC isosterism (Scheme 1), increases the chemical diversity of bioactive molecules^{1,2} by altering the electronic structure with minimal geometric disruption.³⁻⁷ Furthermore, the conjugated molecules and polymers containing three-coordinate boron exhibit interesting optical and electronic properties, making them appropriate for use in functional materials,⁸⁻¹¹ or as ligands in transition-metal complexes.¹²⁻¹⁹ In particular the BN orientation in conjugated molecules with more than one BN unit can develop new antiaromatic systems.²⁰ It is important to highlight that the BN/CC isosterism can also be used as a molecular design strategy to alter the inherent reactivity patterns, which is consistent with the HOMO orbital coefficients determined in direct comparison with all-carbon structures.²¹



Scheme 1: BN isosterism and comparison with the carbonaceous counterpart.

There is an increasing trend to synthesize new conjugated molecules that contain BN units and in that context the 1,3,2-naphthodiazaborole system (Bdan moiety, Scheme 2), where the boron is bonded to 1,8-diaminonaphthalene, is a relevant example where the substitution of the N-B-N unit into the aromatic carbonaceous phenalenyl anion^{22,23} system changes the topology type of the aromatic system, presumably due to a stronger bond localization.^{24,25} Searching for new N-B-N scaffolds, potentially active as functional materials, we designed the preparation of the 9-anthracene naphthodiazaborinine (**1**), where the Bdan unit is bonded to a hindered di-ortho substituted aryl system (9-anthracene).



Scheme 2: Comparative perspective between R-Bdan species and the corresponding phenalenyl anion. Synthesized 9-anthracene naphthodiazaborinine (**1**) compound.

Atomic resolution of molecules by AFM with functionalized tips²⁶ enabled identification of individual unknown molecules.^{27–29} It also opened the possibility to study reaction products formed by on-surface chemistry^{30–35} or atomic manipulation.^{36–40} Dehalogenation^{38,41} and dehydrogenation^{37,40,42–44} by atomic manipulation were demonstrated for several molecular systems.

In this paper, we report the synthesis of **1** and its atomic manipulation and structural probing by AFM. The molecule was produced in a metal-catalyzed reaction. The synthesized molecule is nonplanar. The AFM-based identification of **1** included the transformation of **1** into a planar molecule by removing those hydrogen atoms that induce steric hindrance. The dehydrogenation was achieved with atomic

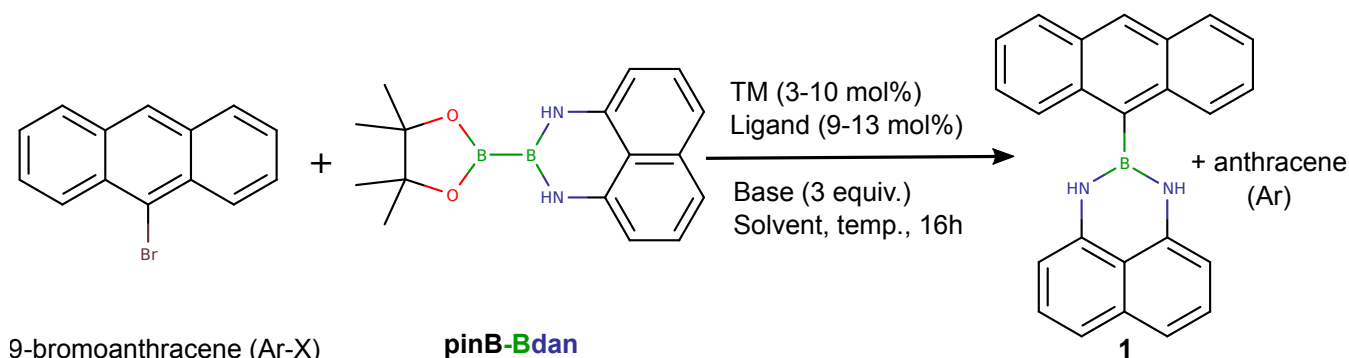
manipulation. This route represents a direct method for scanning probe microscopy techniques to identify the structure of nonplanar molecules.^{32,45}

Results and discussion

Synthesis of 9-anthracene naphthodiazaborinine

In contrast to the well-established Miyaura borylation of aryl halides with diboronate esters as reagents (bis(pinacolato)diboron = B_2pin_2 and others),^{46–56} the analogous direct introduction of Bdan boryl units from HBdan is much less explored.⁵⁷ In fact, it was only recently that a chemoselective transfer of Bdan units from (pin)B-B(dan) to a series of aryl halides has been reported.⁵⁸ However, as far as we are aware, not a single example of Bdan transfer to a bulky di-ortho-substituted aryl halide has been described. Hence, a series of metal-catalyzed direct Bdan borylation reactions of 9-bromoanthracene were conducted to prepare 9-anthracene naphthodiazaborinine (**1**). Initial catalytic conditions were examined with 3 mol% of $Pd_2(dba)_3$, 9 mol% of the Buchwald ligand XPhos, and KOAc as the base (Table 1, entry 1). This catalytic system promoted a complete conversion of the diboron reagent and the formation of **1** in 66% NMR yield. The reaction also produced anthracene (Ar) as byproduct. Attempts to increase the percentage of product **1** formation by changing the reaction temperature (from 100 °C to 70 °C) or using an stoichiometric amount of 9-bromoanthracene versus (pin)B-B(dan), were unsuccessful (Table 1, entries 2,3). Adjusting the 9-bromoanthracene/(pin)B-B(dan) ratio to 1/1.5 led to an improved NMR yield formation of **1** (82%), with 76% of isolated yield (Table 1, entry 4). Notably, the $CuI/nBu_3P/KOtBu$ combination, an alternative, well-established borylation method in the literature,⁵⁹ did not show significant catalytic activity even when the more reactive 9-iodoanthracene was used (Table 1, entries 5 and 6). Noteworthy, **1** is the first Bdan-borylated compound arising from a

Table 1: Conditions for the metal-catalyzed Bdan transfer to 9-bromoanthracene.^a



entry	metal	ligand	base	ArX/(pin)B-B(dan)	temp. (°C)	conv. [%]	Ar NMR yield(%) ^b	1 NMR yield [%] ^b
1	Pd ₂ (dba) ₃	XPhos ^c	KOAc	1/0.8	100	100	27	66
2	Pd ₂ (dba) ₃	XPhos	KOAc	1/0.8	70	77	23	51
3	Pd ₂ (dba) ₃	XPhos	KOAc	1/1	100	70	22	48
4	Pd₂(dba)₃	XPhos	KOAc	1/1.5	100	85	3	82[76]^d
5	CuI	nBu ₃ P	KOtBu	1/1.5	r.t.	62	54	8
6 ^e	CuI	nBu ₃ P	KOtBu	1/1.5	r.t.	84	73	9

^aReaction conditions: 9-bromoanthracene (0.2 mmol), (pin)B-B(dan) (0.8-1.5 equiv.), Pd₂(dba)₃ (3 mol%), XPhos (9 mol%), KOAc (3 equiv.), 1,4-dioxane (0.86 mL), at 100 °C for 16 h.; ^bYields were determined by ¹H NMR analysis of the crude reaction mixture using ferrocene as an internal standard.; ^cBuchwald ligand.; ^dIsolated yield.; ^e9-iodoanthracene was used as ArX.

di-ortho-substituted aryl halide.

AFM analysis

Compound **1** was deposited onto a Cu(111) single crystal, which was partially covered by double layer NaCl islands (referred to as NaCl(2ML)).

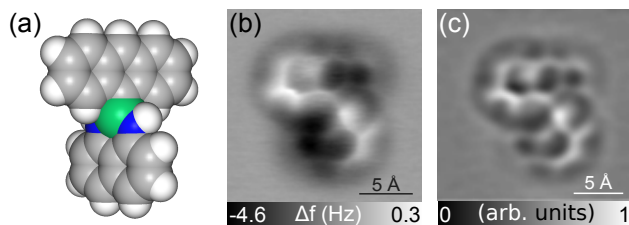


Figure 1: (a) Molecular model, owing to steric hindrance **1** is nonplanar. (b) Constant-height ($\Delta z = +1.2$ Å) AFM frequency shift map recorded with CO tip at 5 K and $V = 0$. (c) Laplace-filtered image of (b).

A constant-height AFM image of **1** adsorbed on Cu(111) is shown in Fig. 1b. The image

was recorded in constant-height mode with a CO-functionalized tip (CO tip)^{26,60} at $\Delta z = +1.2$ Å. The tip height Δz is defined with respect to the STM set-point at $I_t = 1$ pA and sample bias voltage $V = 0.1$ V above Cu(111). In Fig. 1b, the left edge of the anthracenyl head and the right part of the naphthodiazaborinine unit appear with bright contrast, indicating repulsive interactions caused by an increased adsorption height of these parts of the molecule.^{37,45} Owing to the steric hindrance between the H atoms bound to the N atoms and the closest hydrogens of the anthracenyl unit, the molecule is nonplanar (see model in Fig. 1a). Because of the 3D shape of the molecule, its structure could not be determined unambiguously from the image presented in Fig. 1b alone. The structure even remained unclear after Laplace filtering (see Fig. 1c). Only after planarization of the molecule as described in the next section could we conclude that the molecule imaged in Fig. 1b is **1** adsorbed in the geometry indicated in Fig. 1a.

Tip-induced dehydrogenation

To planarize the molecule and to determine its structure unambiguously, we decided to remove the H atoms that cause steric hindrance (see Fig. 2). Dehydrogenation was induced by increasing the bias voltage in constant-height mode until a sudden change in the tunneling current occurred. We positioned the tip with open feedback loop at $\Delta z = -4.5 \text{ \AA}$ above the center of the molecule and ramped the bias voltage from +0.1 V to +4 V. At typically $V = +3.0 \text{ V}$ we observed a sudden drop in the tunneling current indicating a manipulation event.

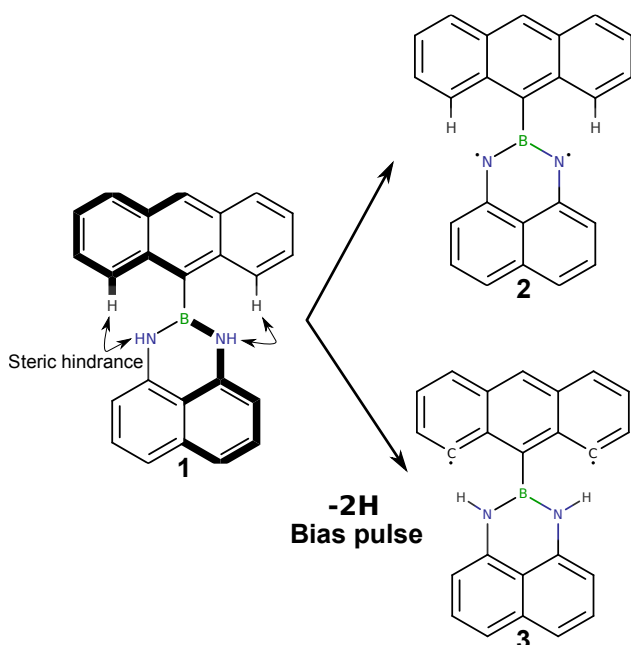


Figure 2: Radical formation and planarization via dehydrogenation: removal of the hydrogen atoms allows the molecule to adapt a planar adsorption geometry.

After the tip-induced reaction, to investigate the outcome, constant-height AFM imaging with a CO tip was performed. As a result of the manipulation the entire molecule could be imaged with atomic resolution and the symmetric appearances of the anthracenyl and the naphthodiazaborinine groups indicate a planar adsorption geometry (see Fig. 3). The steric hindrance could have been eliminated by removing the hydrogens either from the N atoms or from the closest C atoms of the anthracenyl

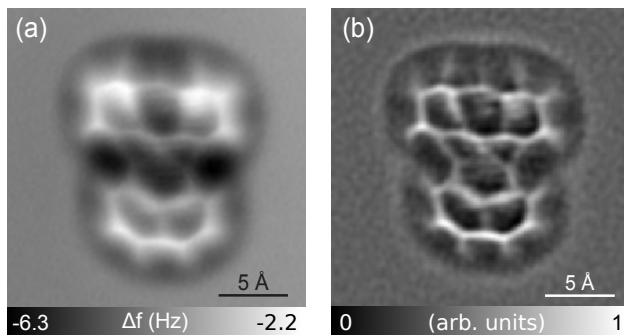


Figure 3: (a) Constant-height ($\Delta z = +2.5 \text{ \AA}$) AFM image with CO tip at $V = 0$ taken after the tip-induced reaction of **1** on Cu(111). (b) The same image after Laplace filtering.

unit (see **2** and **3** in Fig. 2, respectively). However, the exact location of the dehydrogenation cannot be explicitly determined from Fig. 3.

To clarify the mechanism of the planarization, we probed the orbital structure of the manipulated molecule. A two-monolayer-thick NaCl film was used to electronically decouple the molecule from the metal substrate.⁶¹ On NaCl the molecule could be also dehydrogenated at a similar bias as on Cu(111). We were able to image the manipulated molecule at its first negative ion resonance. At increased negative biases, the molecule started to move before the bias voltage reached the energy of its positive ion resonance. The negative ion resonance started to dominate the STM contrast at voltages higher than $V = +1.3 \text{ V}$ (see Fig. 4). In the measurement, the highest orbital density is observed above the naphthodiazabori-

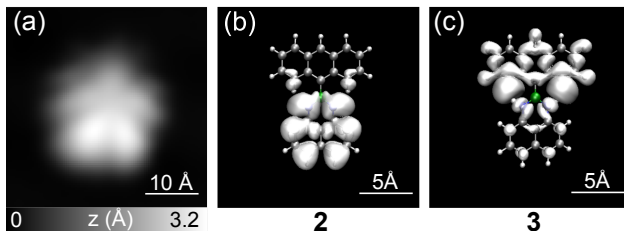


Figure 4: (a) STM measurement of product after dehydrogenation of **1** on NaCl(2ML)/Cu(111) with a metal tip ($V = +1.3 \text{ V}$ and $I = 0.5 \text{ pA}$). (b, c) Calculated density of lowest unoccupied orbitals of the dehydrogenated molecule **2** and **3**, respectively.

nine part, whereas the anthracenyl head of the molecule exhibits only a faint contrast. Our DFT calculations (for more details, see supplementary informations) show that the orbitals with the lowest unoccupied character are located at the naphthodiazaborinine in the case of **2** (see Fig. 4b), whereas they shift to the anthracenyl head in the case of **3** (see Fig. 4c). Therefore we can conclude that the dehydrogenation took place at the N sites. With this knowledge we can unambiguously assign the compound imaged in Fig. 3 as **2** and the compound imaged in Fig. 1 as **1**.

The Laplace-filtered image (Fig. 3b) shows apparent bonds between the N atoms and the closest C atoms of the anthracene unit. The contrast at this position is unlikely to originate from any kind of bonding configuration. Therefore, we attribute this feature to artifacts that are related to the CO tilting at the tip, which is known to produce sharp features that appear similar as bonds at the positions of ridges of the potential.^{45,62–65}

Conclusion

We presented the synthesis of a naphthodiazaborole, namely, 9-anthracene naphthodiazaborinine (**1**), from a di-ortho substituted aryl halide. The yield has been maximized by adjusting the 9-bromoanthracene/(pin)B-B(dan) stoichiometry. The structure of the molecule synthesized was probed via atomic force microscopy and atomic manipulation.

We demonstrated that planarization by atomic manipulation is a possible route for extending molecular identification by AFM to nonplanar molecular systems that are difficult to be probed with AFM directly.

Methods

Measurements were performed using a home-built combined STM and AFM operating in ultrahigh vacuum (base pressure below 10^{-10} mbar) at a temperature of 5 K. The bias voltage V was applied to the sample. The AFM is based on a qPlus sensor⁶⁶ (stiffness

$k = 1800$ N/m, eigenfrequency $f_0 = 29664$ Hz, quality factor $Q = 2 \times 10^5$) operated in frequency-modulation mode.⁶⁷ The PtIr tip was cut to length and sharpened using a focused ion beam setup. The oscillation amplitude was 0.5 \AA to maximize the lateral resolution.⁶⁸ A Cu(111) single crystal was cleaned by several sputtering and annealing cycles. Ultrathin NaCl films were grown by thermal evaporation of NaCl on Cu(111) at a sample temperature of about 270 K. Defect-free (100)-terminated islands of mainly two atomic layers were formed.⁶⁹ Low coverages of **1** and CO molecules were adsorbed at sample temperatures below 10 K. CO tips were prepared by picking up a single CO molecule from NaCl.²⁶

Acknowledgement We thank B. Schuler, S. Fatayer, N. Moll and R. Allenspach for discussions. We acknowledge financial support from the European Research Council Advanced Grant CEMAS (agreement no. 291194), the European Union project PAMS (610446) and the Initial Training Network QTea (317485) programs. This research was supported by the Spanish Ministerio de Economía y Competitividad (MINECO) through projects CTQ2013-43395P and CTQ2013-50219-EXP.

Supporting Information Available: This material is available free of charge via the Internet at <http://pubs.acs.org/>.

References

1. Zhou, H. B.; Nettles, K. W.; Bruning, J. B.; Kim, Y.; Joachimiak, A.; Sharma, S.; Carlson, K. E.; Stossi, F.; Katzenellenbogen, B. S.; Katzenellenbogen, J. A. Elemental Isomerism: A Boron-Nitrogen Surrogate for a Carbon-Carbon Double Bond Increases the Chemical Diversity of Estrogen Receptor Ligands. *Chem. Biol.* **2007**, *14*, 659–669.
2. Knack, D. H.; Marshall, J. L.; Harlow, G. P.; Dudzik, A.; Szaleniec, M.; Liu, S.-Y.; Heider, J. BN/CC Isosteric Compounds as Enzyme Inhibitors: N- and B-Ethyl-1,2-azaborine Inhibit Ethyl-

- benzene Hydroxylation as Nonconvertible-Substrate Analogues. *Angew. Chem. Int. Ed.* **2013**, *52*, 2599–2601.
- Spielvogel, B. F.; Wojnowich, L.; Das, M. K.; McPhail, A. T.; Hargrave, K. D. Boron Analogues of Amino Acids. Synthesis and Biological Activity of Boron Analogues of Betaine. *J. Am. Chem. Soc.* **1976**, *98*, 5702–5703.
 - Spielvogel, B. F.; Das, M. K.; McPhail, A. T.; Onan, K. D.; Hall, I. H. Boron Analogues of the α -Amino Acids. Synthesis, X-ray Crystal Structure, and Biological Activity of Ammonia-Carboxyborane, the Boron Analogue of Glycine. *J. Am. Chem. Soc.* **1980**, *102*, 6343–6344.
 - Ito, H.; Yumura, K.; Saigo, K. Synthesis, Characterization, and Binding Property of Isoelectronic Analogues of Nucleobases, B(6)-Substituted 5-Aza-6-borauracils and -thymines. *Org. Lett.* **2010**, *12*, 3386–3389.
 - Marwitz, A. J. V.; Matus, M. H.; Zakharov, L. N.; Dixon, D. A.; Liu, S.-Y. A Hybrid Organic/Inorganic Benzene. *Angew. Chem. Int. Ed.* **2009**, *48*, 973–977.
 - Abbeya, E. R.; Liu, S. BN Isosteres of Indole. *Org. Biomol. Chem.* **2013**, *11*, 2060–2069.
 - Weber, L.; Böhling, L. The Role of 2,3-dihydro-1-H-1,3,2-diazaboroles in Luminescent Molecules. *Coord. Chem. Rev.* **2015**, *284*, 236–275.
 - Weber, L.; Werner, V.; Fox, M. A.; Marder, T. B.; Schwedler, S.; Brockhinke, A.; Stammler, H.-G.; Neumann, B. Synthetic, Structural, Photophysical and Computational Studies of π -Conjugated bis- and tris-1,3,2-Benzodiazaboroles and Related bis(boryl) Dithiophenes. *Dalton Trans.* **2009**, 1339–1351.
 - Weber, L.; Kahlert, J.; Böhling, L.; Brockhinke, A.; Stammler, H. G.; Neumann, B.; Harder, R. A.; Lowb, P. J.; Fox, M. A. Electrochemical and Spectroelectrochemical Studies of C-benzodiazaboroly-ortho-carboranes. *Dalton Trans.* **2013**, *42*, 2266–2281.
 - Weber, L. E.; Eickhoff, D.; Marder, T. B.; Fox, M. A.; Low, P.; Dwyer, A. D.; Tozer, D. J.; Schwedler, S.; Brockhinke, A.; Stammler, H.-G. *et al.* Experimental and Theoretical Studies on Organic D- π -A Systems Containing Three-Coordinate Boron Moieties as Both π -Donor and π -Acceptor. *Chem. Eur. J.* **2012**, *18*, 1369–1382.
 - Weber, L.; Schnieder, M.; Lönnecke, P. Alkali Metal Reduction of 2-Halogeno- and 2-Thiolato-2,3-Dihydro-1H-1,3,2-Diazaboroles. *J. Chem. Soc., Dalton Trans.* **2001**, 3459–3464.
 - Weber, L. The Chemistry of 1,3,2-Diazaborolines (2,3-dihydro-1H-1,3,2-Diazaboroles). *Coord. Chem. Rev.* **2001**, *215*, 39–77.
 - Segawa, Y.; Yamashita, M.; Nozaki, K. Boryllithium: Isolation, Characterization, and Reactivity as a Boryl Anion. *Science* **2006**, *314*, 113–115.
 - Weber, L. Recent Developments in the Chemistry of 1,3,2-Diazaborolines-(2,3-Dihydro-1H-1,3,2-Diazaboroles). *Coord. Chem. Rev.* **2008**, *252*, 1–31.
 - Yamashita, M.; Nozaki, K. Boryllithium: A Novel Boron Nucleophile and its Application in the Synthesis of Borylmetal Complexes. *Pure Appl. Chem.* **2008**, *80*, 1187–1194.
 - Segawa, Y.; Yamashita, M.; Nozaki, K. Syntheses of PBP Pincer Iridium Complexes: A Supporting Boryl Ligand. *J. Am. Chem. Soc.* **2009**, *131*, 9201–9203.
 - Jones, M. D. N-Heterocyclic Carbene Analogues with Low-Valent Group 13 and Group 14 Elements: Syntheses, Structures, and Reactivities of a New Generation of Multitalented Ligands. *Chem. Rev.* **2011**, *111*, 354–396.

19. Weber, L. Modern 1,3,2-Diazaborole Chemistry – A Metamorphosis from Electrophilic to Nucleophilic Boron. *Eur. J. Inorg. Chem.* **2012**, 5595–5609.
20. Wang, X.-Y.; Narita, A.; Feng, X.; Müllen, K. B₂N₂-Dibenzo[a,e]pentalenes: Effect of the BN Orientation Pattern on Antiaromaticity and Optoelectronic Properties. *J. Am. Chem. Soc.* **2015**, *137*, 7668–7671.
21. Ishibashi, J. S. A.; Marshall, J. L.; Mazzière, A.; Lovinger, G. J.; Li, B.; Zakharov, L. N.; Dargelos, A.; Gracia, A.; Chrostowska, A.; Liu, S.-Y. Two BN Isosteres of Anthracene: Synthesis and Characterization. *J. Am. Chem. Soc.* **2014**, *136*, 15414–15421.
22. Pogodin, S.; Agranat, I. Theoretical Notions of Aromaticity and Antiaromaticity: Phenalenyl Ions versus Fluorenyl Ions. *J. Org. Chem.* **2007**, *72*, 10096–10107.
23. Cyranski, M. A.; Havenith, R. W. A.; Dobrowolski, M. A.; Gray, B. R.; M., K. T.; Fowler, P. W.; Jenneskens, The Phenalenyl Motif: A Magnetic Chameleon. *Chem. Eur. J.* **2007**, *13*, 2201–2207.
24. Chrostowska, A.; Xu, S.; Mazziere, A.; Boknevitc, K.; Li, B.; Abbey, E. R.; Dargelos, A.; Graciaa, A.; Liu, S.-Y. UV-Photoelectron Spectroscopy of BN Indoles: Experimental and Computational Electronic Structure Analysis. *J. Am. Chem. Soc.* **2014**, *136*, 11813–11820.
25. Sagan, F.; Piekos, L.; Andrzejak, M.; Mitoraj, M. P. From Saturated BN Compounds to Isoelectronic BN/CC Counterparts: An Insight from Computational Perspective. *Chem. Eur. J.* **2015**, *21*, 15299–15307.
26. Gross, L.; Mohn, F.; Moll, N.; Liljeroth, P.; Meyer, G. The Chemical Structure of a Molecule Resolved by Atomic Force Microscopy. *Science* **2009**, *325*, 1110–1114.
27. Gross, L.; Mohn, F.; Moll, N.; Meyer, G.; Ebel, R.; Abdel-Mageed, W. M.; Jaspars, M. Organic Structure Determination Using Atomic-resolution Scanning Probe Microscopy. *Nat. Chem.* **2010**, *2*, 821–825.
28. Hanssen, K. Ø.; Gross, L.; Schuler, B.; Jaspars, M.; Williams, A. J.; Isaksson, J.; Demissie, T. B.; Hansen, E.; Andersen, J. H.; Svenson, J. *et al.* A Combined Atomic Force Microscopy and Computational Approach for the Structural Elucidation of Breitfussin A and B: Highly Modified Halogenated Dipeptides from *Thuiaria breitfussi*. *Angew. Chem. Int. Ed.* **2012**, *51*, 12238–12241.
29. Schuler, B.; Meyer, G.; Peña, D.; Mullins, O. C.; Gross, L. Unraveling the Molecular Structures of Asphaltenes by Atomic Force Microscopy. *J. Am. Chem. Soc.* **2015**, *137*, 9870–9876.
30. Oteyza, D. G.; Gorman, P.; Chen, Y. C.; Wickenburg, S.; Riss, A.; Mowbray, D. J.; Etkin, G.; Pedramrazi, Z.; Tsai, H. Z.; Rubio, A. *et al.* Direct Imaging of Covalent Bond Structure in Single-Molecule Chemical Reactions. *Science* **2013**, *340*, 1434–1437.
31. Riss, A.; Wickenburg, S.; Gorman, P.; Tan, L. Z.; Tsai, H.-Z.; de Oteyza, D. G.; Chen, Y.-C.; Bradley, A. J.; Ugeda, M. M.; Etkin, G. *et al.* Local Electronic and Chemical Structure of Oligo-acetylene Derivatives Formed Through Radical Cyclizations at a Surface. *Nano Lett.* **2014**, *14*, 2251–2255.
32. Albrecht, F.; Pavliček, N.; Herranz-Lancho, C.; Ruben, M.; Repp, J. Characterization of a Surface Reaction by Means of Atomic Force Microscopy. *J. Am. Chem. Soc.* **2015**, *137*, 7424–7428.
33. Rogers, C.; Chen, C.; Pedramrazi, Z.; Omrani, A. A.; Tsai, H.-Z.; Jung, H. S.; Lin, S.; Crommie, M. F.; Fischer, F. R. Closing the Nanographene Gap: Surface-Assisted

- Synthesis of Peripentacene from 6,6 \ddagger -Bipentacene Precursors. *Angew. Chem. Int. Ed.* **2015**, *54*, 15143–15146.
34. Dienel, T.; Kawai, S.; Söde, H.; Feng, X.; Müllen, K.; Ruffieux, P.; Fasel, R.; Gröning, O. Resolving Atomic Connectivity in Graphene Nanostructure Junctions. *Nano Lett.* **2015**, *15*, 5185–5190.
 35. Kawai, S.; Saito, S.; Osumi, S.; Yamaguchi, S.; Foster, A. S.; Spijker, P.; Meyer, E. Atomically Controlled Substitutional Boron-Doping of Graphene Nanoribbons. *Nat. Commun.* **2015**, *6*, 8098.
 36. Mohn, F.; Repp, J.; Gross, L.; Meyer, G.; Dyer, M. S.; Persson, M. Reversible Bond Formation in a Gold-Atom–Organic-Molecule Complex as a Molecular Switch. *Phys. Rev. Lett.* **2010**, *105*, 266102.
 37. Schuler, B.; Liu, W.; Tkatchenko, A.; Moll, N.; Meyer, G.; Mistry, A.; Fox, D.; Gross, L. Adsorption Geometry Determination of Single Molecules by Atomic Force Microscopy. *Phys. Rev. Lett.* **2013**, *111*, 086101.
 38. Pavliček, N.; Schuler, B.; Collazos, S.; Moll, N.; Pérez, D.; Guitián, E.; Meyer, G.; Peña, D.; Gross, L. On-surface Generation and Imaging of Arynes by Atomic Force Microscopy. *Nature Chem.* **2015**, *7*, 623–628.
 39. Schuler, B.; Fatayer, S.; Mohn, F.; Moll, N.; Pavliček, N.; Meyer, G.; Pena, D.; Gross, L. Reversible Bergman Cyclization by Atomic Manipulation. *Nat. Chem.* **2016**, *8*, 220–224.
 40. Lit, J.; Boneschanscher, M. P.; Vanmaekelbergh, D.; Ijäs, M.; Uppstu, A.; Ervasti, M.; Harju, A.; Liljeroth, P.; Swart, I. Suppression of Electron–vibron Coupling in Graphene Nanoribbons Contacted via a Single Atom. *Nat. Commun.* **2013**, *4*, 2023.
 41. Hla, S.-W.; Bartels, L.; Meyer, G.; Rieder, K.-H. Inducing All Steps of a Chemical Reaction with the Scanning Tunneling Microscope Tip: Towards Single Molecule Engineering. *Phys. Rev. Lett.* **2000**, *85*, 2777–2780.
 42. Lauhon, L. J.; Ho, W. Single-Molecule Chemistry and Vibrational Spectroscopy: Pyridine and Benzene on Cu(001). *J. Phys. Chem. A* **2000**, *104*, 2463–2467.
 43. Zhao, A.; Li, Q.; Chen, L.; Xiang, H.; Wang, W.; Pan, S.; Wang, B.; Xiao, X.; Yang, J.; Hou, J. G. *et al.* Controlling the Kondo Effect of an Adsorbed Magnetic Ion Through Its Chemical Bonding. *Science* **2005**, *309*, 1542–1544.
 44. Baadji, N.; Kuck, S.; Brede, J.; Hoffmann, G.; Wiesendanger, R.; Sanvito, S. Controlled Sequential Dehydrogenation of Single Molecules by Scanning Tunneling Microscopy. *Phys. Rev. B* **2010**, *82*, 115447.
 45. Pavliček, N.; Fleury, B.; Neu, M.; Niedenführ, J.; Herranz-Lancho, C.; Ruben, M.; Repp, J. Atomic Force Microscopy Reveals Bistable Configurations of Dibenzo[a,h]thianthrene and their Interconversion Pathway. *Phys. Rev. Lett.* **2012**, *108*, 086101.
 46. Ishiyama, T.; Murata, N.; Miyaura, N. Palladium(0)-Catalyzed Cross-Coupling Reaction of Alkoxydiboron with Haloarenes: A Direct Procedure for Arylboronic Esters. *J. Org. Chem.* **1995**, *60*, 7508–7510.
 47. Crawford, A. G.; Liu, Z.; Mkhaliid, I. A. I.; Thibault, M.-H.; Schwarz, N.; Alcaraz, A.; Steffen; Collings, J. C.; Batsanov, A. S.; Howard, J. A. K.; Marder, T. B. Synthesis of 2- and 2,7-Functionalized Pyrene Derivatives: An Application of Selective C-H Borylation. *Chem. Eur. J.* **2012**, *18*, 5022–5035.
 48. Mkhaliid, I. A. I.; Barnard, J. H.; Marder, T. B.; Murphy, J. M.; Hartwig, J. F. C–H Activation for the Construction of C–B Bonds. *Chem. Rev.* **2010**, *110*, 890–931.

49. Hartwig, J. F. Borylation and Silylation of C–H Bonds: A Platform for Diverse C–H Bond Functionalizations. *Acc. Chem. Res.* **2012**, *45*, 864–873.
50. Bose, S. K.; Deifenberger, A.; Eichhorn, A.; Steel, P. G.; Lin, Z.; Marder, T. B. Zinc-Catalyzed Dual C–X and C–H Borylation of Aryl Halides. *Angew. Chem. Int. Ed.* **2015**, *54*, 11843–11847.
51. Ishiyama, T.; Ishida, K.; Miyaura, N. Synthesis of Pinacol Arylboronates via Cross-Coupling Reaction of Bis(pinacolato)diboron with Chloroarenes Catalyzed by Palladium(0)-Tricyclohexylphosphine Complexes. *Tetrahedron* **2001**, *57*, 9813–9816.
52. Fürstner, A.; Seidel, G. Microwave-Assisted Synthesis of Pinacol Boronates from Aryl Chlorides Catalyzed by a Palladium/Imidazolium Salt System. *Org. Lett.* **2002**, *4*, 541–543.
53. Xu, C.; Gong, J. F.; Song, M. P.; Wu, Y. J. Catalysis of the Coupling Reaction of Aryl Chlorides with Bis(pinacolato)diboron by Tricyclohexylphosphine-Cyclopalladated Ferrocenylimine Complexes. *Transition Met. Chem.* **2009**, *34*, 175–179.
54. Molander, G. A.; Trice, S. L. J.; Dreher, S. D. Palladium-Catalyzed, Direct Boronic Acid Synthesis from Aryl Chlorides: A Simplified Route to Diverse Boronate Ester Derivatives. *J. Am. Chem. Soc.* **2010**, *132*, 17701–17703.
55. Kawamorita, S.; Ohmiya, T.; T., I.; Sawamura, M. Palladium-Catalyzed Borylation of Sterically Demanding Aryl Halides with a Silica-Supported Compact Phosphane Ligand. *Angew. Chem. Int. Ed.* **2011**, *50*, 8363–8366.
56. Molander, G. A.; Trice, S. L. J.; Kennedy, S. M. Palladium-Catalyzed Borylation of Aryl and Heteroaryl Halides Utilizing Tetrakis(dimethylamino)diboron: One Step Greener. *Org. Lett.* **2012**, *14*, 4814–4817.
57. Iwadate, N.; Suginome, M. Synthesis of Masked Hoareneboronic Acids via Iridium-Catalyzed Aromatic C–H Borylation with 1,8-Naphthalenediaminoborane (danBH). *J. Organomet. Chem.* **2009**, *694*, 1713–1717.
58. Xu, L.; Li, P. Direct Introduction of a Naphthalene-1,8-diamino Boryl [B(dan)] Group by a Pd-Catalysed Selective Boryl Transfer Reaction. *Chem. Commun.* **2015**, *51*, 5656–5659.
59. Kleeberg, C.; Dang, L.; Lin, Z.; Marder, T. B. E. A Facile Route to Aryl Boronates: Room-Temperature, Copper-Catalyzed Borylation of Aryl Halides with Alkoxy Diboron Reagents. *Angew. Chem. Int. Ed.* **2009**, *48*, 5350–5354.
60. Bartels, L.; Meyer, G.; Rieder, K. H. The Evolution of CO Adsorption on Cu(111) as Studied with Bare and CO-Functionalized Scanning Tunneling tips. *Surf. Sci.* **1999**, *432*, L621–L626.
61. Repp, J.; Meyer, G.; Stojković, S. M.; Gourdon, A.; Joachim, C. Molecules on Insulating Films: Scanning-Tunneling Microscopy Imaging of Individual Molecular Orbitals. *Phys. Rev. Lett.* **2005**, *94*, 086101.
62. Hapala, P.; Kichin, G.; Wagner, C.; Tautz, F. S.; Temirov, R.; Jelínek, P. Mechanism of High-Resolution STM/AFM Imaging with Functionalized Tips. *Phys. Rev. B* **2014**, *90*, 155455.
63. Hämäläinen, S. K.; van der Heijden, N.; van der Lit, J.; den Hartog, S.; Liljeroth, P.; Swart, I. Intermolecular Contrast in Atomic Force Microscopy Images without Intermolecular Bonds. *Phys. Rev. Lett.* **2014**, *113*, 155455.
64. Sweetman, A. M.; Jarvis, S. P.; Sang, H.; Lekkas, I.; Rahe, P.; Wang, Y.; Wang, J.; Champness, N. R.; Kantorovich, L.; Moriarty, P. Mapping the Force Field of a Hydrogen-bonded Assembly. *Nat. Commun.* **2014**, *5*, 3931.

65. Jarvis, S. Resolving Intra- and Inter-Molecular Structure with Non-Contact Atomic Force Microscopy. *Int. J. Mol. Sci.* **2015**, *16*, 19936.
66. Giessibl, F. J. Atomic Resolution on Si(111)-(7×7) by Noncontact Atomic Force Microscopy with a Force Sensor Based on a Quartz Tuning Fork. *Appl. Phys. Lett.* **2000**, *76*, 1470–1472.
67. Albrecht, T. R.; Grütter, P.; Horne, D.; Rugar, D. Frequency Modulation Detection Using High-Q Cantilevers for Enhanced Force Microscope Sensitivity. *J. Appl. Phys.* **1991**, *69*, 668–673.
68. Giessibl, F. J. Advances in Atomic Force Microscopy. *Rev. Mod. Phys.* **2003**, *75*, 949–983.
69. Bennewitz, R.; Baratoff, A.; Barwich, V.; Meyer, E.; Bammerlin, M.; Güntherodt, H. J.; Loppacher, C.; Guggisberg, M.; Baratoff, A. Ultrathin Films of NaCl on Cu(111): a LEED and Dynamic Force Microscopy Study. *Surf. Sci.* **1999**, *438*, 289–296.