University of Groningen

On-Surface Formation of Cumulene by Dehalogenative Homocoupling of Alkenyl gem-Dibromides

Sun, Qiang; Tran, Bay V.; Cai, Liangliang; Ma, Honghong; Yu, Xin; Yuan, Chunxue; Stöhr, Meike; Xu, Wei

Published in:
Angewandte Chemie - International Edition

DOI:
[10.1002/anie.201706104](https://doi.org/10.1002/anie.201706104)

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Final author's version (accepted by publisher, after peer review)

Publication date:
2017

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Sun, Q., Tran, B. V., Cai, L., Ma, H., Yu, X., Yuan, C., Stöhr, M., & Xu, W. (2017). On-Surface Formation of Cumulene by Dehalogenative Homocoupling of Alkenyl gem-Dibromides. *Angewandte Chemie - International Edition*, 56(40), 12165-12169. <https://doi.org/10.1002/anie.201706104>

Copyright

Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license. More information can be found on the University of Groningen website: <https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment>.

Take-down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): <http://www.rug.nl/research/portal>. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

On-surface formation of cumulene by dehalogenative homocoupling of alkenyl gem-dibromides

Qiang Sun,¹ Bay V. Tran,² Liangliang Cai,¹ Honghong Ma,¹ Xin Yu,¹ Chunxue Yuan,¹ Meike Stöhr^{2,*} and Wei Xu^{1,*}

¹Interdisciplinary Materials Research Center and College of Materials Science and Engineering, Tongji University, Shanghai 201804, P. R. China

²Zernike Institute for Advanced Materials, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands

*To whom correspondence may be addressed. E-mail: xuwei@tongji.edu.cn and m.a.stohr@rug.nl

The on-surface activation of carbon-halogen groups represents an efficient route to produce radicals for constructing various hydrocarbons as well as carbon nanostructures. To the best of our knowledge, the so far employed halide precursors have only one halogen attached to a carbon atom. It is thus of particular interest to study the effect of attaching more than one halogen atom to a carbon atom with the aim of producing multiple unpaired electrons. Herein, by introducing an alkenyl gem-dibromide, we have successfully fabricated cumulene products on a Au(111) surface by dehalogenative homocoupling reactions. The reaction products and pathways were unambiguously characterized by the combination of high-resolution scanning tunneling microscopy (STM) and non-contact atomic force microscopy (nc-AFM) measurements together with state-of-the-art density functional theory (DFT) calculations. This study further supplements the database of on-surface synthesis strategies, and importantly, it provides a facile manner for incorporation of more complicated carbon scaffoldings into surface nanostructures.

The recently developed on-surface synthesis strategy has gained increasing attention due to its prospects in constructing - starting from organic monomers - covalently interlinked, extended nanostructures, which are of scientific and technological interest for future applications owing to their promising electronic properties and high mechanical stability.¹⁻⁶ In general, most of the on-surface reactions follow pathways different from their counterparts in solution because of the effects of the surface: the reactions are confined in two dimensions and the possible catalytic surface activity.⁷⁻¹⁴ Consequently, unexpected reactions have been surprisingly discovered in on-surface synthesis experiments,¹⁵⁻²² and thus, this strategy has opened up a way for the fabrication of a plethora of novel surface nanostructures which may be hardly obtained by traditional solution methods. Among others, the atomically precise synthesis of carbon nanostructures such as graphene nanoribbons²³⁻³⁰ and other hydrocarbons like alkanes, dienes and diynes has become a hot topic within the field of on-surface synthesis.³¹⁻³⁵ In particular, it has been demonstrated that the thermally-induced dehalogenation of pre-defined C-X groups (X stands for halogens) provides an efficient route to produce radicals for subsequent C-C couplings on surfaces.^{14,24,27} Besides, some reactive intermediates, like arynes,³⁶ aromatic diradicals and a highly strained ten-membered diyne³⁷ have been artificially generated on surfaces by cleaving C-X bonds with the aid of STM manipulations and thereby, yielding radicals. However, to the best of our knowledge, the so far employed halide precursors have only one halogen atom attached to a carbon atom, which can merely produce one unpaired electron at the

carbon site. Thus, it is of particular interest to investigate dehalogenative reactions of germinal dihalide precursors on surfaces, to explore and thereby, extend our fundamental understandings of on-surface C–C coupling reactions with two unpaired electrons.

Figure1 | Schematic illustration showing the formation of cis- and trans-cumulene products through dehalogenative C–C homocoupling reactions of the alkenyl gem-dibromide molecular precursor bBVBP.

Recently, we have investigated the dehalogenative homocoupling of alkenyl bromides on Cu(110).³⁸ In light of this previous study, we have designed and synthesized a molecular precursor functionalized with an alkenyl gem-dibromide group (named bBVBP, the synthesis and its full name are detailed in the supporting information), as shown in Figure1. Herein, by the combination of high-resolution STM and nc-AFM measurements, we investigate the debromination and the subsequent C–C homocoupling reactions of alkenyl gem-dibromides on a Au(111) surface. We unambiguously identify from the single-bond resolved nc-AFM images the formation of cis- and trans-cumulene products having three consecutive C–C double bonds as schematically shown in Figure 1. These findings are explained by successive debromination reactions followed by subsequent C–C homocouplings on the basis of our DFT-based transition-state search calculations. This study extends the database of on-surface dehalogenative C–C homocoupling reactions by introducing gem-dibromides. Importantly, it provides a facile manner to generate two unpaired electrons by a surface-assisted successive C–Br bond activation resulting in the formation of C–C double bonds (specifically, cumulenes in this case) based on C–C homocouplings. This represents a new strategy for incorporating more complicated carbon scaffoldings into tailor-made surface nanostructures.

Figure 2 | Formation of cumulene on Au(111). **a** Overview STM image showing the formation of discrete motifs after deposition of bBVBP molecules on Au(111) at room temperature. **b** Close-up STM image allowing to identify two typical dimer structures, labeled as D-1 and D-2, respectively. Scanning parameters: $V_t = -2.1$ V, $I_t = 20$ pA. **c,e** High-resolution STM images of the dimer structures D-1 and D-2, respectively, together with the equally scaled DFT relaxed models overlaid on top. **d,f** Corresponding frequency shift AFM images of the two dimer structures. The red arrows indicate the cumulene groups. Scale bars: 5 Å.

Results and discussion

After deposition of bBVBP molecules on Au(111) held at room temperature, we observed the formation of discrete structural motifs as well as small aggregations on the surface as shown in the overview STM image in Figure 2a. A closer inspection of the STM image allows to identify that most of the molecules reside at the fcc regions or elbow sites of the herringbone reconstruction of the Au(111) surface. The two most abundant motifs observed are shown in Figure 2b: one displays a linear shape with two lobes (labeled D-1) and the other displays a curved shape with two lobes as well (labeled D-2). Based on the STM appearances and dimensions of the two lobes, we infer that both D-1 and D-2 are composed of two bBVBP molecules. According to our previous study,³⁸ such D-1 and D-2 dimers are speculated to be the products of dehalogenative C-C homocoupling reactions on the surface. However, the bond configurations within the dimer structures cannot be precisely determined based on the STM images. Note that we occasionally observe a trimer structure exhibiting three lobes (as shown in FigureS1), and a tetramer structure having four lobes (vide infra).

To further characterize the chemical structures of the D-1 and D-2 dimers, we utilized single-bond resolved nc-AFM imaging in conjunction with DFT calculations. First, we focus on the D-1 structure. From the high-resolution STM image and the corresponding frequency shift AFM image (Figure 2c and 2d, respectively), we identify that the two biphenyl groups are linked together, which confirms the formation of a dimer structure. More importantly, a sharp line with a homogeneous contrast connecting the two biphenyl groups (indicated by a red arrow in Figure 2d) can be clearly discerned. Generally, such features observed in nc-AFM images usually indicate chemical bonds within a molecule.³⁹⁻⁴² Based on the above analyses, we unambiguously assign this characteristic line feature to the cumulene group having three consecutive C–C double bonds as illustrated in the DFT relaxed model in Figure 2c. In line with D-1, we also imaged D-2 with STM and nc-AFM as shown in Figure 2e and 2f, respectively. We could again clearly resolve the two biphenyl groups linked together by a similar line feature (indicated by a red arrow in Figure 2f). This implies the formation of the cumulene group within the D-2 structure as well (cf. DFT relaxed model in Figure 2e). According to the isomeric configurations of D-1 and D-2, we assign D-1 to the trans-cumulene product, and D-2 to the cis one.

Figure 3 DFT calculations of both cumulenes on Au(111). **a,b** DFT relaxed models of trans- and cis-cumulene products on Au(111). **c,d** Calculated electron density maps of both products, which are cut along a plane parallel to the Au surface above the molecules. The cumulene groups are indicated by red arrows. **e,f** The corresponding simulated constant-height nc-AFM images.

To further verify the formation of the cumulene group, we performed further DFT calculations to construct the relevant structural models of both trans- and cis-cumulene products on Au(111), and calculate the corresponding charge densities. As shown in Figure 3a and 3b, both cumulene products adopt flat-lying geometries on Au(111) except the slight tilt of the benzene rings with respect to each other,^{43,44} and the cumulene group adopts for both cases a linear geometry. The average molecular heights are measured to be 3.1 Å from the DFT models. It has been previously stated that the intramolecular contrast resolved by nc-AFM can be modeled by considering the charge density of the targeted molecules, because the atomic contrast is a consequence of Pauli repulsion.^{45,46} Thus, we calculated the charge density for both cumulene products adsorbed on Au(111), and the cuts along the planes parallel to the surface are shown in Figure 3c and 3d. From these charge density map slices, we can clearly distinguish the biphenyl groups, and more importantly, the cumulene groups exhibit a linear contrast in good agreement with their nc-AFM features. In addition, on the basis of the optimized models, we performed the corresponding nc-AFM simulations by an online modeling software,⁴⁵ which also agree well with our experimental results (cf. Figure 3e and 3f).

Figure 4 | The tetramer structure. **a,b** High-resolution STM image and the corresponding frequency shift nc-AFM image of a tetramer structure on Au(111). **c** Charge density difference of the structure showing the intermolecular interactions. The isosurface value is at $0.006 \text{ e}\text{\AA}^{-3}$. Scale bars: 5 Å.

Interestingly, we also occasionally observed some tetramers consisting of four lobes on the Au surface. From the combination of high-resolution STM and the nc-AFM measurements (Figure 4a and 4b), we could determine that such a tetramer structure is actually composed of two cis-cumulene dimers. DFT calculations show that these two cis-cumulene dimers are stabilized by a relatively weak intermolecular interaction ($\text{CH}\cdots\pi$) as reflected by the charge density difference map (Figure 4c), and the binding energy is determined to be 0.18 eV. Note that it is hard to determine from the STM image alone the covalent or non-covalent character between two cis-cumulene dimers within this tetramer structure. Thanks to the simultaneously acquired nc-AFM image, the non-covalent feature between the two dimers could be identified. On the other hand, in comparison with the cis-cumulene dimer structure, it further corroborates the formation of the cumulene group on the surface.

To understand the dehalogenative homocoupling of alkenyl gem-dibromides from a fundamental point of view, we performed extensive calculations to explore the possible reaction pathways from molecular precursors to cumulene products on the Au(111) surface. As

shown in Figure 5, we have proposed reasonable reaction pathways of the successive C–Br bond activations followed by subsequent C–C homocouplings on the Au(111) surface (for the calculations, a simplified bBVBP molecule was used, for which the biphenyl group was replaced by a phenyl one). As shown in Figure 5a, the energy barriers for the successive debrominations on Au(111) are calculated to be 0.91 eV and 0.63 eV, respectively, and the whole dehalogenation reaction is exothermic by 0.52 eV. The energy barrier for the subsequent C–C homocoupling was calculated to be 0.90 eV as depicted in Figure 5b, along with a reaction energy of 1.39 eV. All of these energy barriers are in reasonable agreement with the experimental conditions and could well account for the observed formation of the cumulene products on Au(111).

Figure 5 | Reaction pathways for the formation of the trans-cumulene. **a** The DFT-calculated reaction pathway for the successive C–Br bond activations of the simplified bBVBP molecule on Au(111). **b** The DFT-calculated reaction pathway from the debrominated intermediates to a cumulene product on Au(111). The structural models of the initial (IS), transition (TS), intermediate (Int) and final states (FS) along the pathways are also shown.

Conclusion

In conclusion, from the combination of high-resolution UHV-STM and nc-AFM imaging together with DFT calculations, we successfully fabricated cumulene products on the Au(111) surface by introducing dehalogenative homocoupling reactions of alkenyl gem-dibromides. Additionally, with the help of DFT calculations we were able to suggest a reasonable reaction pathway for all the steps involved to obtain from the starting monomers to the final cumulene products. It has been recently reported that the elusive aryne has been generated by STM tip excitation on the NaCl/Cu(111) surface and the formed aryne represents a curved cumulene resonance structure.³⁶ Another comparable case is the observation of a cumulene moiety as one of the transient intermediates along an enediyne coupling and cyclization reaction.⁴⁸ Our study sets itself apart from these results since we succeeded for the first time to create linear cumulene structures in a highly controllable fashion. More importantly, it may shed light on the fabrication of increasingly complicated carbon scaffoldings by utilizing the on-surface synthesis strategy.

Methods

STM characterization and sample preparation. The measurements were carried out in a two-chamber ultrahigh vacuum system with a base pressure of 5×10^{-11} mbar. The system houses a combined STM / AFM (Scienta Omicron) set-up operated at a temperature of 5K. The Au(111) substrate was prepared by several cycles of 1.5 keV Ar^+ sputtering followed by annealing to 800 K, resulting in clean and flat terraces separated by monatomic steps. After the system was thoroughly degassed, the bBVBP molecules were sublimed from the molecular evaporator onto the substrate held at room temperature. The sample was thereafter transferred within the UHV chamber to the microscope. The AFM is based on a qPlus sensor operated in frequency-modulation mode, and all AFM images were acquired in constant-height mode using CO-functionalized tips (resonance frequency ~ 21 kHz; spring constant: 1800 Nm^{-1} ; Q-factor: ~ 24000 ; oscillation amplitude: ~ 100 pm; bias voltage: 0V).

DFT calculation. The calculations were performed in the framework of DFT by using the Vienna Ab Initio Simulation Package (VASP) code.^{47,48} The projector augmented wave method was used to describe the interaction between ions and electrons,^{49,50} and the Perdew-Burke-Ernzerhof generalized gradient approximation exchange–correlation functional was employed.⁵¹ Van der Waals corrections to the PBE density functional were also included using the DFT-D3 method of Grimme.⁵² The atomic structures were relaxed using the conjugate gradient algorithm scheme as implemented in VASP until the forces on all unconstrained atoms were $\leq 0.03 \text{ eV/\AA}$ for geometry optimization. The climbing-image nudged elastic band was applied to locate the transition state⁵³ and the reaction pathway was optimized until the forces acting to the path were converged typically to $\leq 0.05 \text{ eV/\AA}$. For the transition state searches for C–Br bond scissions on Au(111), 13 images along the pathway are used to locate each transition state. For the transition state searches for the following C–C coupling on Au(111), 18 images along the pathway are used to locate the transition state.

References

- [1] de Oteyza, D. G. et al, Direct imaging of covalent bond structure in single-molecule chemical reactions. *Science*, **340**, 1434 (2013).
- [2] Lafferentz, L. et al, Conductance of a single conjugated polymer as a continuous function of its length. *Science*, 323,1193 (2009).
- [3] Sun, Q. et al, On-surface formation of one-dimensional polyphenylene through Bergman cyclization. *J. Am. Chem. Soc.* **135**, 8448 (2013).
- [4] Grill, L. et al, Nano-architectures by covalent assembly of molecular building blocks. *Nat. Nanotechnol.* **2**, 687 (2007).
- [5] Franc, G. & Gourdon, A. Covalent networks through on-surface chemistry in ultra-high vacuum: state-of-the-art and recent developments. *Phys. Chem. Chem. Phys.* **13**,14283 (2011).
- [6] Zhang, X., Zeng, Q. & Wang, C. On-surface single molecule synthesis chemistry: a promising bottom-up approach towards functional surfaces. *Nanoscale* **5**, 8269 (2013).
- [7] Sun, Q. et al, Bottom-up synthesis of metalated carbyne. *J. Am. Chem. Soc.*, **138**, 1106 (2016).
- [8] Zhong, D. et al, Linear alkane polymerization on a gold surface. *Science*, **334**, 213 (2011).
- [9] Sun, Q., Zhang, C., Kong, H., Tan, Q. & Xu, W. On-surface aryl–aryl coupling via selective C–H activation. *Chem. Commun.* **50**, 11825 (2014).
- [10] Wiengarten, A. et al, Surface-assisted dehydrogenative homocoupling of porphine molecules. *J. Am. Chem. Soc.* **136**, 9346 (2014).
- [11] Kocic, N. et al, Control of Reactivity and Regioselectivity for On-Surface Dehydrogenative Aryl–Aryl Bond Formation. *J. Am. Chem. Soc.* **138**, 5585 (2016).
- [12] Li, Q. et al, Surface-Controlled Mono/Diselective ortho C–H Bond Activation. *J. Am. Chem. Soc.* **138**, 2809 (2016).
- [13] Han, P. et al, Bottom-up graphene-nanoribbon fabrication reveals chiral edges and enantioselectivity. *ACS Nano* **8**, 9181 (2014).
- [14] Fan, Q. et al, Surface-Assisted Organic Synthesis of Hyperbenzene Nanotroughs. *Angew. Chem., Int. Ed.* **52**, 4668 (2013).

- [15] Gao, H. Y. et al, Decarboxylative polymerization of 2, 6-naphthalenedicarboxylic acid at surfaces. *J. Am. Chem. Soc.* **136**, 9658 (2014).
- [16] Liu, J. et al, Lattice-directed formation of covalent and organometallic molecular wires by terminal alkynes on Ag surfaces. *ACS Nano* **9**, 6305 (2015).
- [17] Sun, Q. et al, On-surface formation of two-dimensional polymer via direct C–H activation of metal phthalocyanine. *Chem. Commun.*, **51**, 2836 (2015).
- [18] Wang, W., Shi, X., Wang, S., Van Hove, M. A. & Lin, N. Single-molecule resolution of an organometallic intermediate in a surface-supported Ullmann coupling reaction. *J. Am. Chem. Soc.* **133**, 13264 (2011).
- [19] Kawai, S. et al, Thermal control of sequential on-surface transformation of a hydrocarbon molecule on a copper surface. *Nat. Commun.* **7**, 12711 (2016).
- [20] Zhou, H. et al, Direct visualization of surface-assisted two-dimensional diyne polycyclotrimerization. *J. Am. Chem. Soc.* **136**, 5567 (2014).
- [21] Cirera, B. et al, Thermal selectivity of intermolecular versus intramolecular reactions on surfaces. *Nat. Commun.* **7**, 11002 (2016).
- [22] Matena, M., Riehm, T., Stöhr, M., Jung, T. A., & Gade, L. H. Transforming surface coordination polymers into covalent surface polymers: linked polycondensed aromatics through oligomerization of N-heterocyclic carbene intermediate. *Angewandte Chemie*, **120**, 2448 (2008).
- [23] Ruffieux, P. et al, On-surface synthesis of graphene nanoribbons with zigzag edge topology. *Nature* **531**, 489 (2016).
- [24] Cai, J. et al, Atomically precise bottom-up fabrication of graphene nanoribbons. *Nature*, **466**, 470 (2010).
- [25] Zhang, H. et al, On-surface synthesis of rylene-type graphene nanoribbons. *J. Am. Chem. Soc.* **137**, 4022 (2015).
- [26] Chen, Y. C. et al, Tuning the band gap of graphene nanoribbons synthesized from molecular precursors. *ACS Nano*, **7**, 6123 (2013).
- [27] Pham, T. A., Tran, B. V., Nguyen, M.-T. & Stöhr, M. Chiral-selective formation of one-dimensional polymers based on Ullmann-type coupling: the role of the metallic substrate. *Small* **13**, 1603675 (2017).
- [28] Kawai, S. et al, Atomically controlled substitutional boron-doping of graphene nanoribbons. *Nat. Commun.* **6**, 8098 (2015).
- [29] Kimouche, A. et al, Ultra-narrow metallic armchair graphene nanoribbons. *Nat. Commun.* **6**, 10177 (2015).
- [30] Basagni, A. et al, Molecules–oligomers–nanowires–graphene nanoribbons: a bottom-up stepwise on-surface covalent synthesis preserving long-range order. *J. Am. Chem. Soc.* **137**, 1802 (2015).
- [31] Sun, Q. et al, Single-molecule insight into Wurtz reactions on metal surfaces. *Phys. Chem. Chem. Phys.* **18**, 2730 (2016).
- [32] Cai, L., Sun, Q., Zhang, C., Ding, Y. & Xu, W. Dehydrogenative homocoupling of alkyl chains on Cu (110). *Chem. Eur. J.* **22**, 1918 (2016).
- [33] Sun, Q. et al, Dehydrogenative homocoupling of terminal alkenes on copper surfaces: a route to dienes. *Angew. Chem. Int. Ed.* **54**, 4549 (2015).
- [34] Sun, Q., Cai, L., Ma, H., Yuan, C. & Xu, W. Dehalogenative homocoupling of terminal alkynyl bromides on Au (111): Incorporation of acetylenic scaffolding into surface nanostructures. *ACS Nano* **10**, 7023 (2016).
- [35] Cirera, B. et al, Synthesis of extended graphdiyne wires by vicinal surface templating. *Nano Lett.* **14**, 1891 (2014).
- [36] Pavlíček, N. et al, On-surface generation and imaging of arynes by atomic force microscopy. *Nat. Chem.* **7**, 623 (2015).
- [37] Schuler, B. et al, Reversible Bergman cyclization by atomic manipulation. *Nat. Chem.* **8**, 220 (2016).
- [38] Sun, Q., Cai, L., Ma, H., Yuan, C. & Xu, W. The stereoselective synthesis of dienes through dehalogenative homocoupling of terminal alkenyl bromides on Cu (110). *Chem. Commun.* **52**, 6009 (2016).
- [39] van der Lit, J., Di Cicco, F., Hapala, P., Jelinek, P. & Swart, I. Submolecular resolution imaging of molecules by atomic force microscopy: the influence of the electrostatic force. *Phys. Rev. Lett.* **116**, 096102 (2016).
- [40] Gross, L., Mohn, F., Moll, N., Liljeroth, P., & Meyer, G. *Science* **325**, 1110-1114 (2009).
- [41] Iwata, K. et al, Chemical structure imaging of a single molecule by atomic force microscopy at room temperature. *Nat. Commun.* **6**, 7766 (2015).
- [42] He, Y. et al, Fusing tetrapyrroles to graphene edges by surface-assisted covalent coupling. *Nat. Chem.* **9**, 33 (2017).
- [43] Braun, K. F. & Hla, S. W. Probing the conformation of physisorbed molecules at the atomic scale using STM manipulation. *Nano letters* **5**, 73 (2005).
- [44] Klappenberger, F. et al, Uniform π -system alignment in thin films of template-grown dicyanobenzene-oligophenyls. *Adv. Funct. Mater.* **21**, 1631 (2011).

- [45] Hämäläinen, S. K. et al, Intermolecular contrast in atomic force microscopy images without intermolecular bonds. *Phys.Rev.Lett.***113**, 186102 (2014).
- [46] Moll, N., Gross, L., Mohn, F., Curioni, A. & Meyer, G. The mechanisms underlying the enhanced resolution of atomic force microscopy with functionalized tips. *New J. Phys.*, **2010**, 12, 125020.
- [47] Hapala, P. et al, Mechanism of high-resolution STM/AFM imaging with functionalized tips. *Phys. Rev. B***90**, 085421 (2014).
- [48] Riss, A. et al, Imaging single-molecule reaction intermediates stabilized by surface dissipation and entropy. *Nat. Chem.***8**, 678 (2016).
- [49] Kresse, G. & Hafner, J. *Ab initio* molecular dynamics for open-shell transition metals. *Phys. Rev. B***48**, 13115 (1993).
- [50] Kresse, G. & Furthmüller, J. Efficient iterative schemes for *ab initio* total-energy calculations using a plane-wave basis set. *Phys. Rev. B***54**, 11169 (1996).
- [51] Blöchl, P. E. Projector augmented-wave method. *Phys. Rev. B***50**, 17953 (1994).
- [52] Kresse, G. & Joubert, D. From ultrasoft pseudopotentials to the projector augmented-wave method. *Phys. Rev. B***59**, 1758 (1999).
- [53] Perdew, J. P., Burke, K. & Ernzerhof, M. Generalized gradient approximation made simple. *Phys. Rev. Lett.***77**, 3865 (1996).
- [54] Grimme, S., Antony, J., Ehrlich, S. & Krieg, H. A consistent and accurate *ab initio* parametrization of density functional dispersion correction (DFT-D) for the 94 elements H-Pu. *J. Chem. Phys.* **132**, 154104 (2010).
- [55] Henkelman, G., Uberuaga, B. P. & Jonsson, H. A climbing image nudged elastic band method for finding saddle points and minimum energy paths. *J. Chem. Phys.* **113**, 9901 (2000).

Acknowledgements

The authors acknowledge financial support from the National Natural Science Foundation of China (21473123, 21622307, 51403157) as well as from Netherlands Organization for Scientific Research (NWO, Chemical Sciences, Vidi Grant No. 700.10.424) and the European Research Council (ERC-2012-StG 307760-SURFPRO).

Author contributions

W.X. conceived the experiments. Q.S., B.T. and L.C. performed the STM experiments. Q.S., B.T. and M.S. performed AFM measurements. Q.S. performed the calculations. H.M., X.Y. and C.Y. synthesized the molecule. Q.S. and W.X. drafted the paper. All authors discussed the results and commented on the manuscript at all stages.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper at www.nature.com/naturechemistry.

Reprints and permission information is available online at <http://npg.nature.com/reprintsandpermissions/>.

Correspondence and requests for materials should be addressed to W.X. (xuwei@tongji.edu.cn). M.S. (m.a.stohr@rug.nl).