

Cite this: *Chem. Sci.*, 2023, 14, 1403 All publication charges for this article have been paid for by the Royal Society of Chemistry

# On-surface synthesis of non-benzenoid conjugated polymers by selective atomic rearrangement of ethynylarenes†

Alejandro Jiménez-Martín,<sup>‡</sup> Federico Villalobos,<sup>‡</sup> Benjamin Mallada,<sup>ade</sup> Shayan Edalatmanesh,<sup>ade</sup> Adam Matěj,<sup>ade</sup> Juan M. Cuerva,<sup>‡</sup> Pavel Jelínek,<sup>ae</sup> Araceli G. Campaña,<sup>‡</sup> and Bruno de la Torre<sup>‡</sup>

Here, we report a new on-surface synthetic strategy to precisely introduce five-membered units into conjugated polymers from specifically designed precursor molecules that give rise to low-bandgap fulvalene-bridged bisanthene polymers. The selective formation of non-benzenoid units is finely controlled by the annealing parameters, which govern the initiation of atomic rearrangements that efficiently transform previously formed diethynyl bridges into fulvalene moieties. The atomically precise structures and electronic properties have been unmistakably characterized by STM, nc-AFM, and STS and the results are supported by DFT theoretical calculations. Interestingly, the fulvalene-bridged bisanthene polymers exhibit experimental narrow frontier electronic gaps of 1.2 eV on Au(111) with fully conjugated units. This on-surface synthetic strategy can potentially be extended to other conjugated polymers to tune their optoelectronic properties by integrating five-membered rings at precise sites.

Received 23rd August 2022  
Accepted 19th December 2022

DOI: 10.1039/d2sc04722e

rsc.li/chemical-science

## Introduction

The ability to control their characteristics with rational chemical synthesis has made conjugated polymers excellent candidates for technological applications such as light emitting devices, solar cells, organic field-effect transistors, photocatalysts and biosensors.<sup>1,2</sup> These semiconductors and synthetic metals have been generated from a wide range of organic precursors comprising heterocyclic compounds as well as non-benzenoid polycyclic hydrocarbons.<sup>3</sup> The successful synthesis of these non-benzenoid compounds has recently provided profound insights into the electronic properties of antiaromatic and/or open-shell systems.<sup>4–9</sup> For example, these antiaromatic compounds have demonstrated higher charge carrier mobility

than their aromatic counterparts,<sup>10</sup> although the interpretation of these properties is still unclear.<sup>11,12</sup> Unfortunately, conventional wet synthesis of conjugated polymers containing non-benzenoid compounds is difficult in the case of unstable final compounds due to their inherent low solubility, high intrinsic reactivity and the occurrence of undesirable structural defects<sup>13</sup> that prevent complete control of the molecular structure.

On-surface synthesis<sup>14,15</sup> under ultra-high vacuum (UHV) conditions is a promising strategy for synthesizing non-benzenoid compounds. This approach has proven to be ideal for fabricating (macro)molecular architectures with atomic precision and tailored electronic properties.<sup>16</sup> The rational design of precursor molecules and the stabilization offered by single-crystal substrates allow the engineering of specific products, enabling the fine-tuning of their structural and electronic properties,<sup>15</sup> the fabrication of intrinsically reactive molecular structures<sup>7–9,17</sup> and the investigation of rearrangement reactions<sup>18–23</sup> of particular interest for non-benzenoid  $\pi$ -extended nanostructures.<sup>24</sup> It therefore provides unique opportunities to address the scientific challenge of fabricating well-defined conjugated polymers incorporating non-benzenoid components, with the goal of designing chemically robust, low bandgap polymers. Nevertheless, there are only a few reports discussing the on-surface formation of non-benzenoid moieties,<sup>18,25–29</sup> sometimes in conjugated polymers.<sup>8,21,30–35</sup> Most of them have utilized strategies based on oxidative ring closure,<sup>8,36</sup> bond rotation<sup>37</sup> or the use of molecular precursors with embedded 5-membered rings.<sup>38,39</sup> Therefore, it is highly desirable to provide new strategies that allow the controlled

<sup>a</sup>Regional Centre of Advanced Technologies and Materials, Czech Advanced Technology and Research Institute (CATRIN), Palacký University Olomouc, Olomouc 783 71, Czech Republic. E-mail: bruno.de@upol.cz

<sup>b</sup>Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Břehova 7, Prague 1 115 19, Czech Republic

<sup>c</sup>Departamento de Química Orgánica, Universidad de Granada (UGR), Unidad de Excelencia de Química UEQ, C. U. Fuentenueva, Granada 18071, Spain. E-mail: aracelig@ugr.es

<sup>d</sup>J. Department of Physical Chemistry, Faculty of Science, Palacký University, Olomouc 78371, Czech Republic

<sup>e</sup>Institute of Physics, Czech Academy of Sciences, Prague 162 00, Czech Republic

† Electronic supplementary information (ESI) available: Methods, Fig. S1 to S8, synthesis of the material, NMR spectra, MS spectra, single crystal X-ray crystallography, references. See DOI: <https://doi.org/10.1039/d2sc04722e>

‡ These authors contributed equally to this work.

formation and detailed analysis of such non-benzenoid molecules.

Here, we exploited the atomic rearrangement of ethynylarene to cyclopenta-fused polycyclic aromatic hydrocarbons, to give rise to low bandgap fulvalene-bridged bisanthene polymers on an atomically flat Au(111) surface. To this end, we synthesized 9,10-bis(trimethylsilyl)ethynylanthracene and 10,10'-bis(trimethylsilyl)ethynyl-9,9'-bianthracene as precursors (**1** and **4** in Fig. 1, respectively). Each of them was intentionally designed with a dual purpose: (i) to form one-dimensional diethynyl-bridged polymers after homo-coupling of terminal alkynes (Glaser-like coupling) on the surface;<sup>40</sup> and (ii) to favor the selective atomic rearrangement of the linker giving rise to non-benzenoid units.<sup>41</sup> Furthermore, endowing precursors **1** and **4** with trimethylsilyl (TMS) groups allows chemical protection of the compounds and the *in situ* deprotection of such terminal alkynes on-surface under UHV conditions. This strategy offers an alternative to the use of unstable or highly-reactive monomers.<sup>42–44</sup> Using scanning tunneling microscopy and spectroscopy (STM and STS), in combination with non-contact atomic force microscopy (nc-AFM) and density functional theory (DFT) calculations, we analyzed the chemical structure and electronic properties of the reaction products. Importantly, overall, we reveal the successful formation of fulvalene-bridged bisanthene conjugated polymers that exhibit a low bandgap of a measurable value of 1.2 eV.

## Results and discussion

Fig. 1 shows the chemical structure of the precursor molecules **1** and **4**, which we have used in this study. **1** and **4** were synthesized in solution from commercially available 9,10-dibromoanthracene and 10,10'-dibromo-9,9'-bianthracene, respectively, *via* double Sonogashira coupling with trimethylsilylacetylene (see ESI† for details of the synthesis). The corresponding unprotected terminal alkynes 9,10-diethynylanthracene and 10,10'-diethynyl-9,9'-bianthracene

were also synthesized in solution by treatment of **1** and **4** with tetrabutylammonium fluoride. However, we observed that these compounds tend to react or decompose under ambient conditions. Besides, thermo gravimetric analysis (TGA) shows a gradual decomposition of protected **4** at temperatures above the evaporation threshold (Fig. S1†). For this reason, we decided to keep the trimethylsilyl protecting groups and perform *in situ* deprotection prior to the on-surface polymerization.

Sublimation of **1** under UHV conditions on clean Au(111) maintained at room temperature gives rise to self-assembled molecular islands of anthracene units with their remaining TMS groups, as depicted by the STM and nc-AFM images (Fig. 2a, inset) and in perfect agreement with previous reports on Ag(111).<sup>45</sup> The STM images after sample annealing at 225 °C (*cf.* Fig. 2b) reveal that polymerization of **1** has been triggered, leading to the formation of one-dimensional molecular structures on the surface. In the close-up nc-AFM image recorded with a functionalized CO-tip (Fig. 2c), polymer units were resolved. These consist of anthracene units coupled by diethynyl motifs, confirming the formation of **2**. The two triple bonds are unambiguously distinguishable as bright dots, which is consistent with recent observations on synthesized ethynylene-bridged anthracene polymers<sup>46</sup> and poly(*p*-phenylene ethynylene) molecular wires on Au(111).<sup>47</sup> Interestingly, compared to the reported ethynylene-bridges, diethynyl units increase the electronic bandgap from 1.5 eV<sup>46</sup> to approximately 1.9 eV (see Fig. S2†). In addition, intramolecular rearrangement of **2** is frequently observed, and a significant number of five-membered rings are found in the linkers, giving rise to structure **3**, as shown in Fig. 2c, right. From the STM/AFM images, we inferred that residual hydrogen from the environment chemically passivates the alkynes at the termini of the polymers. The fact that these non-benzenoid units are consistently found in the linkers indicates that they all originated by arrangement of the ethynylene moiety. Indeed, it is clear that along the bridged unit, the 5-membered ring can be found to be coupled to an ethynylene segment, as can be inferred by the presence of the

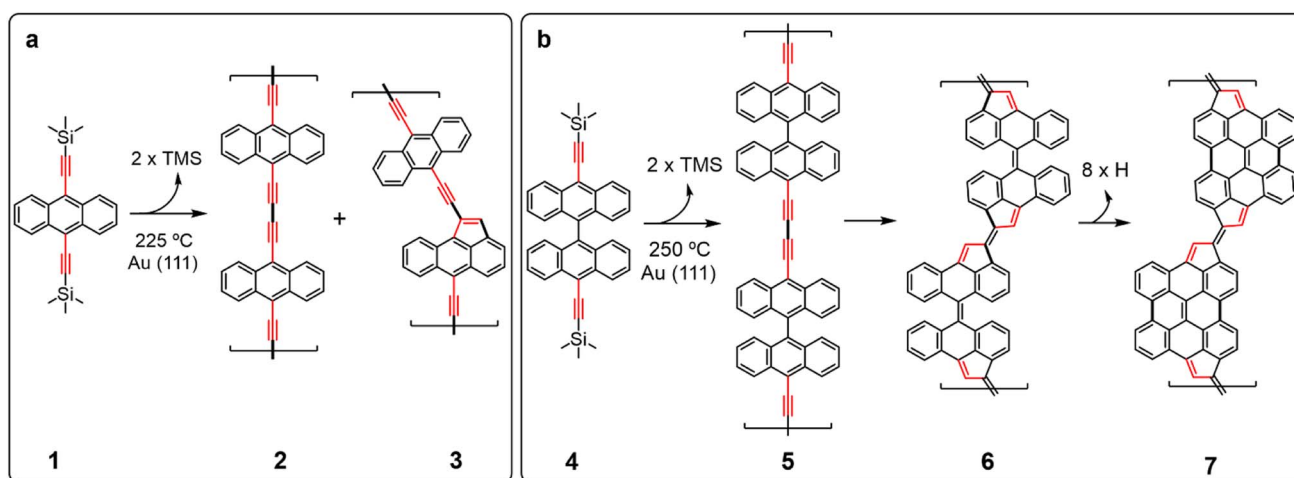
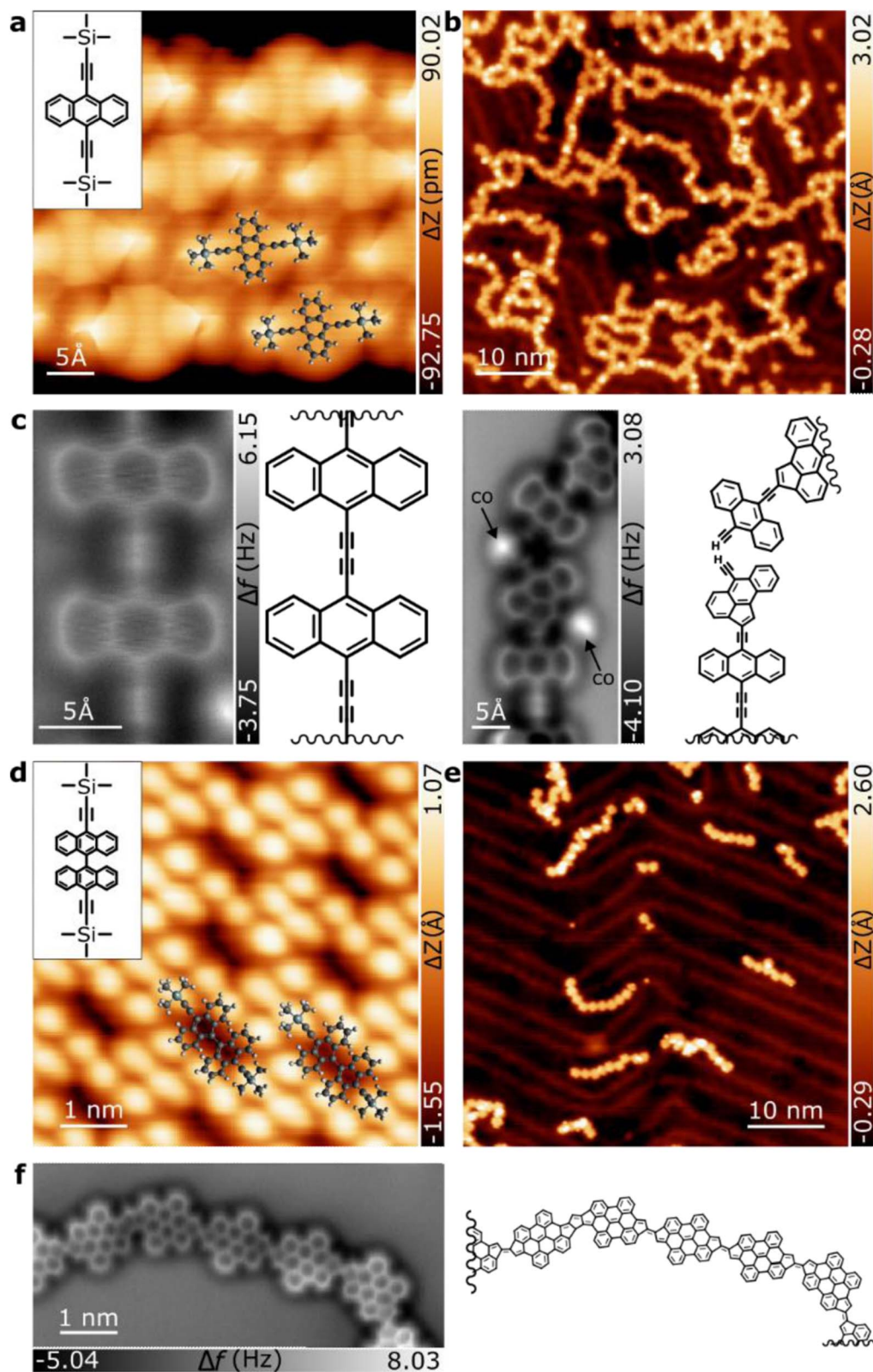


Fig. 1 Scheme of the reaction sequence of (a) anthracene and (b) bianthracene based precursors after being deposited on Au(111) and annealed up to 225 °C and 250 °C, respectively, to produce conjugated polymers incorporating non-benzenoid units.



**Fig. 2** On-surface synthesis of fulvalene-bonded bisanthrene polymers. (a) STM topographic overview with a superimposed model of precursor (1) (top left inset) upon deposition at RT on Au(111) (0.05 V, 0.01 nA). (b) STM topographic overview after thermal annealing at 225 °C (0.1 V, 0.01 nA). (c) nc-AFM detailed images of the one-dimensional molecular structures of (b) including their respective model. The images show the presence of diethynyl bonds and ethynyl-pentagon joints. (d) STM topographic overview with a model of precursor (4) (top left inset) after deposition at RT on Au(111) (−2 V, 0.05 nA). (e) STM topographic overview of the sample after annealing at 250 °C (0.1 mV, 0.02 nA). (f) High-resolution nc-AFM image of a fulvalene-bridged bisanthrene polymer and the corresponding model of the polymer.





Although aromaticity is well understood for benzenoid compounds, the application of these concepts to non-benzenoid systems is not trivial. A better understanding of their “aromatic character” may lead to fruitful theoretical proposals and to the synthesis of novel non-benzenoid conjugated compounds on surfaces. In addition, the aromatic character of a given compound determines the relationship between its constituents and its chemical reactivity or electron delocalization energy.<sup>56</sup> Therefore, it is interesting to analyze the degree of aromaticity and antiaromaticity of the bisanthene-fulvalene polymer. The left panel of Fig. 4d shows the calculated nucleus-independent chemical shift (NICS)<sup>57</sup> of a bisanthene-

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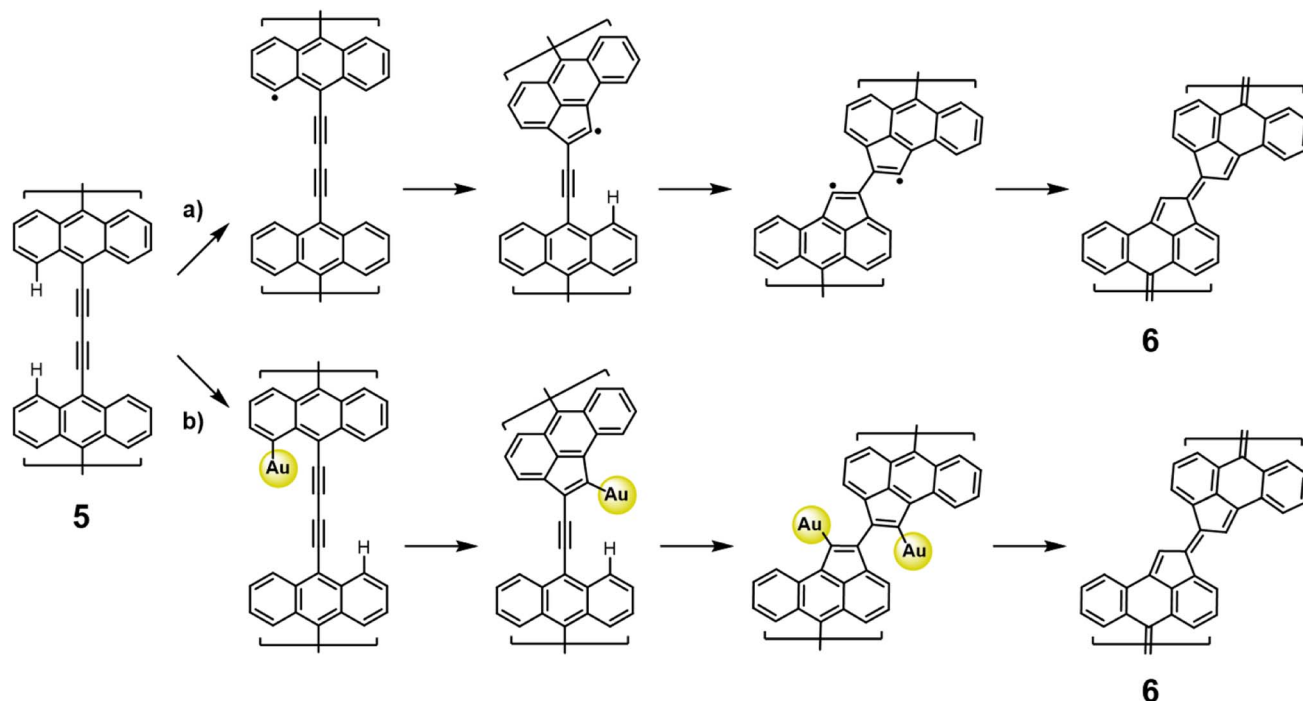


Fig. 3 Proposed reaction mechanism giving rise to fulvalene units. (a) Traditional, and (b) on-surface proposed ethynylarene rearrangement to cyclopenta fused polycyclic aromatic hydrocarbons. An initial hydrogen abstraction is followed by oxidative ring closure and  $\pi$ -electron reconfiguration, while individual gold atoms may stabilize transient radicals.

fulvene dimer passivated by  $H_2$  at the edges to induce the double bond character of the C–C bond connecting two pentagons. Thus, the structure is closed shell since the potential radicals are quenched, at least for the dimer. NICS analysis revealed that the four benzenoid rings at the bisanthene kinks are clearly aromatic, while the central six-membered ring possesses values close to zero, typical of non-aromaticity, thus reproducing well the bond length analysis and corroborating

the resonance form discussed above. On the other hand, in the pentagons of the fulvalene segment, we find positive values for the shielding tensor component ( $-\sigma_{zz}$ ), which may indicate antiaromaticity. Qualitatively, however, those values are close to zero, which may indicate that the pentagons do not participate in the  $\pi$ -conjugation of the system. The deviation of conjugation pathway from zig-zag edge near the fulvalene rings effectively prolongs the conjugation path from 22 to 26 electrons,

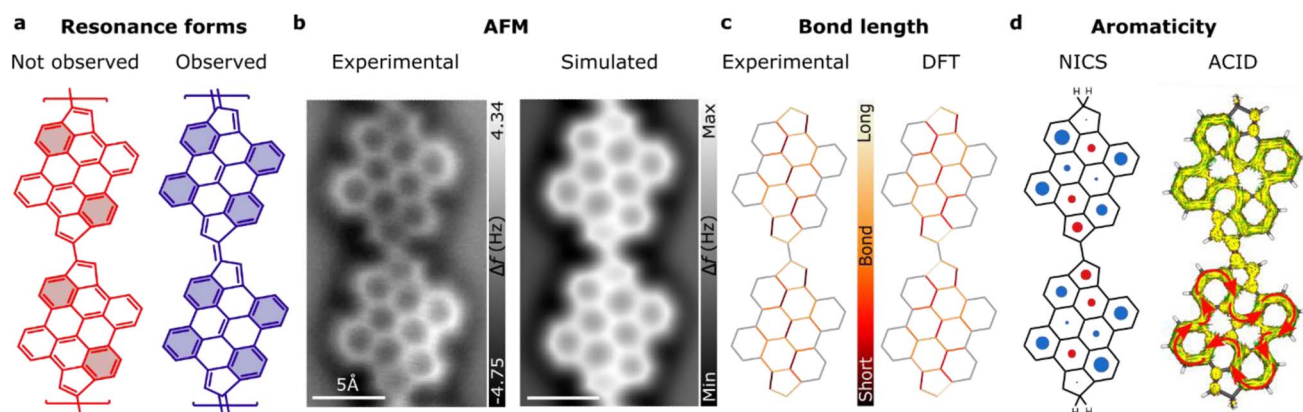


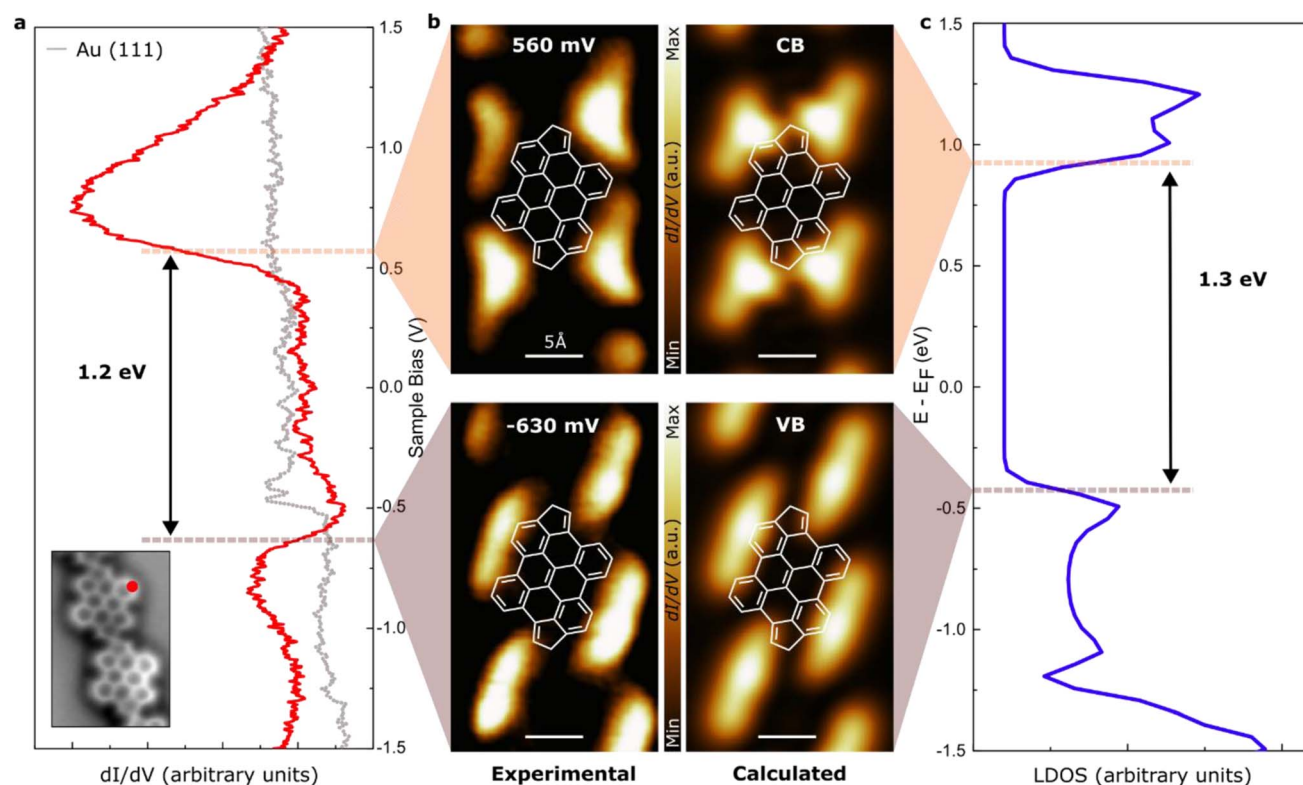
Fig. 4 Resonance and bond analysis of fulvalene-linked polymers. (a) Proposed resonance structures of bisanthene-fulvalene polymers. In blue (red) are the observed (not-observed) resonance forms of the fulvalene-based polymers on the surface (Clar's sextets are highlighted). (b) Experimental (left) and simulated (right) nc-AFM images of fulvalene-bridged one-dimensional structures. (c) Experimental (left) and DFT (right) bond length analysis for a bisanthene-fulvalene dimer. (d) Calculated nucleus-independent chemical shift (NICS) of a fulvalene dimer (left) and calculation of the induced current density (ACID) revealing the  $\pi$ -conjugation of the system (right). The diameter of the circle features corresponds to the qualitative aromatic/antiaromatic (blue/red) character of the ring (see Table in Fig. S6†).

which explains the positive shielding on the benzene rings. The intensity of positive shielding above fulvene and the central benzene rings is much lower than that of proto-typical anti-aromatic molecules, such as cyclobutadiene and pentalene, so they are considered non-aromatic (see Fig. S7† for the quantitative analysis of NICS calculation for the H and H<sub>2</sub> terminated dimer and tetramer).

To gain further insight into the aromatic character of the polymer, we performed calculations of the anisotropy of the induced current density (ACID)<sup>38</sup> (Fig. 4d right panel). The  $\pi$ -ACID (including only pz orbitals) shows a clear conjugation within each bisanthene unit including 26  $\pi$ -electrons in total. The map reveals the interactions of ring currents of each individual ring, enhancing or suppressing the boundary with the neighboring ring, depending on their mutual orientations. Indeed, it reveals that there is aromatic  $\pi$ -conjugation within bisanthene units with the fulvalene units excluded. The ACID map shows the clockwise direction of the main current ring on the bisanthene periphery, revealing its aromatic character with all  $\pi$ -electrons involved in this current, in agreement with the  $4n + 2$  rule of aromaticity. We found that it is possible to include the fulvene moieties in the global ring current by passivating the dimer edges with H instead of H<sub>2</sub> (see Fig. S8† for the quantitative analysis of ACID calculation for the H and H<sub>2</sub> terminated dimer and tetramer). However, this leads to the

single bond character of the C–C bond connecting the pentagons and an antiaromatic number of  $\pi$ -electrons, which goes against Glidewell and Lloyd's rule and the experimental observations. Conjugation through the linker shows a higher critical isosurface value for the double-bond linker (CIV 0.0395) than for the single-bond linker (CIV 0.0311, not shown), showing higher electron delocalization between the units. To conclude, the fulvalene polymer is aromatic with non-aromatic linkers, resulting in weak conjugation between units.

Finally, to access the intrinsic electronic characteristics of the bisanthene-fulvalene polymers, we performed a set of scanning tunneling microscopy and spectroscopy experiments. A voltage-dependent differential conductance spectrum ( $dI/dV$  vs.  $V$ ) acquired on **7** revealed peaks in the density of states (DOS) at  $-630$  mV and  $560$  mV (Fig. 5a). Those peaks arise respectively from hybridization of the polymer valence and conduction bands (VB and CB) with the substrate. Spatial mapping of the  $dI/dV$  signal ( $dI/dV$  maps) at peak positions revealed characteristic features (Fig. 5b) that are well reproduced by the corresponding B3LYP-DFT-calculated  $dI/dV$  maps for an oligomer formed by **7** (Fig. 5c). The  $dI/dV$  map of the VB shows maxima at the lateral edge of the bisanthene moiety, with negligible charge density over the bridge (see Fig. 5b). The  $dI/dV$  map of the CB exhibits states on the empty spaces adjacent to the fulvene bridges (see Fig. 5b). Although DFT calculations could not



**Fig. 5** Electronic structure of fulvalene polymers. (a)  $dI/dV$  conductance spectra of the polymer acquired at the position marked with red in the inset image. The red profile features a gap corresponding to 1.2 eV. (b) Experimental constant current  $dI/dV$  maps (left) and calculated PDOS (right) at the conduction band (top) and valence band (down) onsets. (c) DFT calculated LDOS for fulvalene polymers in the gas phase featuring a bandgap of 1.3 eV.



qualitatively predict the magnitude of the intrinsic bandgap of the polymer<sup>59</sup> (Fig. 5c), they described very well the character of the frontier orbitals of the VB and CB edges of the polymer (*cf.* Fig. S9†). In fact, the excellent agreement between experimental and simulated dI/dV maps validates the character of the frontier orbitals predicted by DFT. Thus, this results in a low bandgap of ~1.2 eV on Au(111). It should be noted that the bandgap value obtained from STS measurements is typically reduced by an additional electron screening imposed by the proximity of a metallic surface with respect to the intrinsic bandgap of the gas-phase polymer.<sup>60</sup> However, in this case, the perfect agreement between experimental and DFT values of the electronic bandgap indicates a low degree of hybridization of the fulvalene-polymer with the metal support.

## Conclusion

In conclusion, by studying the rearrangement of ethynylarene to cyclopenta fused polycyclic aromatic hydrocarbons on surfaces, we have introduced a novel synthetic strategy for the selective incorporation of five-membered rings into conjugated polymers. In particular, trimethylsilylacetylene protection/deprotection is a well-established strategy in solution-phase chemistry, which we believe also has great potential in the area of on-surface chemistry. The successful realization of bisanthene-fulvalene polymers is confirmed by STM and high-resolution nc-AFM analyses. We found that such a polymer exhibits a measurable low band gap of 1.2 eV and a closed-shell electron configuration on Au(111), as demonstrated by STS supported by DFT calculations. We anticipate that our new synthetic strategy will open avenues to fabricating highly demanded covalent polymers on surfaces incorporating non-benzenoid moieties, which are particularly attractive for organic photovoltaics, photodetectors, and ambipolar field-effect transistors.<sup>61–63</sup>

## Data availability

Data will be available on request. CCDC-2193258 contains the supplementary crystallographic data for this paper. More experimental details can be found in the ESI.†

## Author contributions

A. G. C. and B. T. conceived and designed the experiments. A. G. C. and B. T. supervised the project and led the collaboration efforts. A. J.-M., B. M. and B. T. carried out the SPM experiments, obtained the data and performed on-surface reactions. F. V., J. M. C. and A. G. C. synthesized the precursors. The experimental data were analysed by A. J.-M. and B. T., and discussed by all the authors. S. E., A. M. and P. J. performed the theoretical calculations. The manuscript was written by A. J.-M., A. G. C. and B. T. with contributions from all the authors.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

The authors gratefully acknowledge the support of the Operational Programme for Research, Development, and Education of the European Regional Development Fund (Project No. CZ.02.1.01/0.0/0.0/16\_019/0000754), the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program (Grant Agreement 677023), and FEDER/Junta de Andalucía-Consejería de Transformación Económica, Industria, Conocimiento y Universidades (B.FQM.428.UGR20). F. V. thanks Ministerio de Universidades (Spain, FPU18/05938). P. J. and S. E. acknowledge the support of the GACR 20-13692X. B. M. and A. M. acknowledge the support from the Internal Student Grant Agency of the Palacký University in Olomouc, Czech Republic IGA\_PrF\_2022\_026 and IGA\_PrF\_2022\_019, respectively. B. M. further acknowledges the Fischer Scholarship.

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