

Linear carbon chains: ultimate 1D crystals



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This work has been done by



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The outline

- Carbyne: an elusive allotrope of carbon
- Laser ablation and stabilisation of C-chains
- Deposition on a substrate
- TEM and X-ray analysis, Raman spectra
- Low-temperature photoluminescence reveals strong exciton features!
- Conclusions

Carbon hybridization and resulting nano-objects

Pan et al. Sci. Adv. 2015;1:e1500857 30 October 2015

Carbyne: high expectations

452. Adolf Baeyer: Ueber Polyacetylenverbindungen.

[Zweite Mittheilung.] [Aus dem chem. Laboratorium der Akad. der Wissensch. zu München.] (Eingegangen am 14. August.)

In der ersten Abhandlung¹) über diesen Gegenstand ist die Diacetylendicarbonsäure genauer beschrieben worden, während die Abkömmlinge derselben nur kurz erwähnt werden konnten. In der folgenden Mittheilung soll nun diese Lücke ausgefüllt werden.

Bei der vollständigen Reduction der Tetraacetylendicarbonsäure müsste Sebacinsäure erhalten werden. In der That bildet sich auch bei der Behandlung derselben, zuerst mit Zink und Schwefelsäure, dann mit Natriumamalgam eine sehr schwer lösliche, bei 2000 schmelzende Säure, welche durch sehr energische Reduction mit Natriumamalgam in eine bei 130° schmelzende übergeführt wird, die die Eigenschaften der Sebacinsäure zu besitzen scheint. Bei der geringen Menge von Substanz konnte indess die Identität beider Säuren nicht vollkommen festgestellt werden.

Diacetylen, H---CECC---CEEC---H.

Bei der grossen Uebereinstimmung zwischen der Acetylendicarbonsäure und der Diacetylendicarbonsäure konnte man erwarten, aus der letzteren in derselben Weise das Diacetylen abscheiden zu können, wie das Acetylen aus der ersteren.

успехи химии 1982

T. LI

Вып. 5

УДК 661.66, 661.97/99

СТРОЕНИЕ ПОЛИМЕРНОГО УГЛЕРОДА

Мельниченко В. М., Сладков А. М., Никулин Ю. Н.

С позиций науки о полимерах проведен критический анализ экспериментальных работ и модельных представлений по структурной организации различных форм конденсированного углерода. Подчеркнута роль химических межмолекулярных связей (узлов разветвления), ламелярных и других надмолекулярных образований в многоступенчатом процессе пространственного структурирования полимерного углерода. Сделан вывод о существовании, кроме алмазных и графитных, множества других кристаллических форм углерода — регулярных полимеров карбинового или переходного типов. Библиография — 297 ссылок.

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CUMULENE AND POLYYNE ARE SEMICONDUCTORS

The band gap predicted for infinite chains: cumulene $(=C=C=)_n - 0.41eV$ (under high pressure) polyyne $(-C=C-)_n - 1eV$ (atmospheric pressure)

ACS-NANO, **7**(11), 10075 (2013); Synthetic Metals, 17, 557(1987); Nat. Commun. **6**, 6636 (2015)

The problem:

Freestanding linear chains of over 6 atoms are theoretically unstable to bending and folding

They need to be stabilized!

A. G. Whittaker, Carbon: A new view of its high-temperature behavior. *Science* **200**, 763–764 (1978).

Our method of the carbyne synthesis

LASER HEATING OF CARBON TARGET

Jagdish Narayan and Anagh BhaumikJournal of Applied Physics 118, 215303 (2015);
 M. C. Downer et al, International Journal of Thermophysics, Vol. 14, No. 3, 1993

Stablization of linear carbon chains by metal nanoparticles in a solution

First step: laser-ablation in water

THE EXPERIMENTAL CONCEPT

Second step: laser-induced fragmentation of carbon flakes

THE EVOLUTION OF A COLLOIDAL SYSTEM AT DIFFERENT STEPS OF THE EXPERIMENT

RAMAN SPECTRA OF A COLLOIDAL SYSTEMS

Initial amorphous flakes

HR TEM vs X-ray data

Carbon "onion"-structures

Carbyne based metasurfaces

OPTICAL SPECTRA OF IRRADIATION COLLOIDAL SYSTEM

Optical absorption

Photoluminescence spectra

Carbyne deposition

The deposition of monoatomic carbon chains end-capped with Au NPs in the presence of a static electric field 西湖大學

Deposited carbynes on a Au/Pt grid

The X-ray diffraction pattern

The photoluminescence spectrum of a carbyne at T_{room}

The photoluminescence spectrum of a carbyne film deposited on a fused quartz glass substrate (red line) and its fit by a distribution of Gaussian functions corresponding to individual carbon chains of fixed lengths the approximated length distribution of linear parts of the deposited carbon chains extracted from the photoluminescence measurements

Luminescence vs Absorption

Pan et al. Sci. Adv. 2015;1:e1500857 Carbyne with finite length: The one-dimensional sp carbon

Jun Xiao et al **Molecular Luminescence of White Carbon Small** 2017, 1603495

The temperature dependence of PL spectra

The fine structure is visible on the top of wide peaks associated with chains of different lengths The sharp triplet structure repeats itself for chains of different lengths

Excitons are artificial hydrogen atoms formed in semiconductor crystals

The CNT exciton binding energies on the order of 300–400 meV for the tubes with diameters between 6.8 and 9 Å

J. Maultzsch* et all, Excitons in carbon nanotubes, phys. stat. sol. (b) 243, No. 13, 3204 – 3208 (2006) / DOI 10.1002/pssb.200669131

The time-resolved photoluminescence data 🛥 潮 🛧 學

Ab-initio calculation

Molecular orbitals for polyyne C14 - Au13₂ fragments.

Ab-initio calculation

MolecularorbitalsforpolyyneC14H-terminated.Red and blue lobes correspond to positive and negative values

HOMO and LUMO electron densities are spread over the whole chain in the absence of gold anchors at the ends!

The scheme of excitonic transitions in monoatomic polyyne chains

-0《0-0=0-0=0-

номо

PL triplet spectrum

d)

The trion transitions in charged chains, where the left-right symmetry is broken so that the opticel transititoro (X) urs for tweeten eitherathe odigiedgel States state ignidated sprin thad at 3000 led tylon state localiseid at one of the edges (X-) or between the hole state localised at one of the edges and the original LUMO state (X+).

西湖大學

CONCLUSION

- 1. The laser induced fragmentation of colloidal carbon systems leads to the formation of monoatomic linear carbon chains.
- 2. We fabricate monoatomic carbon chains attached to the golden nanoparticles that may serve as electrical contacts. This paves the way to the development of integrated nano-electronics.
- 3. We deposit carbynes on a substrate and demonstrate the HR TEM images of the chains containing over 50 atoms, that is an absolute length record. The diffraction pattern of carbynes confirms their one-dimensional crystal structure that is expected to possess a variety of unique physical properties.

The second stage - fragmentation of carbon particles

LASER HEATING OF CARBON PARTICLES IN A LIQUID MEDIA Maximal temperature Phase diagram

Pressure (Pa)

$$T_{max} = \frac{I_p k_a d}{8\chi},$$

 I_p – peak power 10⁹ W/cm² χ – liquid thermal conductivity d = 100 nm (initial diameter)

Mie-parameter for spherical particles

$$\mathbf{k}_{a} = \mathbf{e}^{\left(-0.2\left[\sqrt{n^{2}+k^{2}}-1\right]\right)} \left(\mathbf{1} - \mathbf{e}^{\left(-\frac{4\pi kd}{\lambda}\right)}\right)$$
$$T_{max} < 5000 \text{K}$$

Giant nonlinear optical responses of carbyne

C. R. Ma, J. Xiao and G. W. Yang//**J. Mater. Chem. C,** 2016, 4, 4692

Formation of π -electron delocalization in carbyne. (A) Process of atomic orbital sp-hybridization. (B) Existence of extensive π electron delocalization in carbyne.

Science Superconductivity in 4 Angstrom Single-Walled Carbon Nanotubes

Z. K. Tang, Lingyun Zhang, N. Wang, X. X. Zhang, G. H. Wen, G. D. Li, J. N. Wang, C. T. Chan, Ping Sheng*

Investigation of the magnetic and transport properties of single-walled smalldiameter carbon nanotubes embedded in a zeolite matrix revealed that at temperatures below 20 kelvin, 4 angstrom tubes exhibit superconducting behavior manifest as an anisotropic Meissner effect, with a superconducting gap and fluctuation supercurrent. The measured superconducting characteristics display smooth temperature variations owing to one-dimensional fluctuations, with a mean-field superconducting transition temperature of 15 kelvin. Statistical mechanic calculations based on the Girzburg-Landau free-energy functional yield predictions that are in excellent agreement with the experiments. K. Lambropoulos, C. Simserides *Phys.Chem.Chem.Phys.*, 2017, 19, 26890

Fig. 1 (a) Dispersion relation [(inset) width of each band and bandgap], (b) eigenspectra for up to N = 60, (c) density of states of polyynic carbynes as a function of the hopping integral ratio $\pm 1/t^2$

Scheme 1. Energy Level Diagram for J-Type Aggregates and H-Type Aggregates^a

^aJ-type aggregates formed by head-to-tail arrangement of adjacent NCD particles, resulting in splitting of excited energy levels into two. The electronic transition to lower excited level is allowed. In contrast, H-type aggregates are formed via side-by-side arrangement of adjacent NCD particles, which result in splitting of excited energy levels into two. The electronic transition to higher level is allowed. Absorption (Abs) of photon and subsequent fluorescence emission (FI) are represented by upward arrow and downward arrow, respectively. Internal conversion (IC) is indicated as dotted downward arrow.

J. S. Anjali Devi et al Solvent Effects: A Signature of J- and H-Aggregate of Carbon Nanodots in Polar Solvents// J. Phys. Chem. A 2019, 123, 7420–7429

(A)

E. Mostaani et al Quasiparticle and excitonic gaps of one-dimensional carbon chains //Phys. Chem. Chem. Phys., 2016, 18, 14810--14821

Fig. 5 (a) Ground-state (GS) DMC energy of polypne as a function of BLA for lattice constant 2.58 Å in different sizes of simulation supercell. The inset shows the ground-state DMC energy of polypne against the lattice constant at a fixed ratio of C=C bond length to lattice constant for 8 primitive cells (p.c.) and a fixed C=C bond length for 16 primitive cells. (b) GS DMC energy of polypne as a function of BLA for lattice constant 2.5817 Å in different sizes of supercell. The minimum of the DMC energy, -306.901(3) eV per primitive cell, is at BLA $b_0 = 0.136(2)$ Å. The inset shows the square modulus $|\psi_0|^2$ of the longitudinal optical phonon ground-state wave function for a supercell composed of 16 primitive cells as a function of BLA.

BLA=abs(L1-L2) L1 – is single bond length L2 – is triple bond length

Fig. 13 DFT-HSE06 band structure of polyyne. The dashed line shows the Fermi energy.

Fig. 14 DFT-HSE06 zero-point correction Δ_{corr} to the excitonic gap of polygne against the reciprocal of the number *n* of primitive cells in the supercell.

Fig. 1 Finite-size error in the total energy of a 1D exciton against the periodic cell length L = an, where a is the lattice constant and n is the number of primitive cells. $R^*_{\infty} = \mu/2$ is the exciton Rydberg and $a^*_0 = 1/\mu$ is the exciton Bohr radius. $\mu = m_{\rm e}m_{\rm h}/(m_{\rm e} + m_{\rm h})$ is the reduced mass of the electron-hole pair.

Fig. 2 Distribution of HOMO and LUMO DFT-PBE eigenvalues of benzene at the static-lattice level (vertical red and green lines) and including the effects of zero-point motion (shaded blue curves).

Structures and electrical transport

Liu M. et al. ACS-nano, **7**(11), 10075 (2013)

GW 0.3 Eg (eV) 0.2 E (eV) 0.1 0 <u>|</u> -0.05 0.2 (¥) BLA (Å) (eV) HSE DA BLA (Å) 0.2 0.1

Figure 1. Carbyne under tension. (a) DFT calculations of stretching energy per unit cell (two atoms) as a function of strain ε . The bond length alternation (b) and electronic density of carbyne (c) without strain and (d) under tension, showing a more pronounced bond alternation in stretched carbyne. (e) GW band gap increase as a function of strain for structures obtained with pure (LDA) and hybrid (HSE) density functionals, the latter predicting a stronger BLA (b). (f) Dependence of GW correction to LDA band gap as a function of bond length alternation.

O. V. Kibis, D. G. W. Parfitt and M. E. Portnoi

PHYSICAL REVIEW B 71, 035411 (2005)

3 2 Δε 1 °⁄/3 -1 -2 -3 -1 $k_{s}a/\pi$

FIG. 3. Electron energy spectrum of a (1,1) CNT in the presence of a transverse electric field $E = \gamma_0 / (ea_{c-c})$ with $\phi = 0$ (solid lines) and without the electric field (dashed lines). The inner pair of vertical dotted lines indicates the first Brillouin zone boundary in the presence of the field, whereas the outer pair corresponds to the first Brillouin zone boundary without the field. $\Delta \varepsilon$ is the Bragg gap opened by the electric field.

Figure 1. Electronic properties of carbyne under strain. (a) Bond length alternation (BLA), band gap (E_g), and Peierls barrier (E_p , inset) as a function of strain in the static case. Points, DFT calculation results. Lines, fitting based on the analytical model. The fitting is performed in the [-5%, 5%] strain range assuming that the lattice stiffness decreases linearly with strain, and is done independently for BLA and E_g . The E_p line in the inset is computed based on the BLA fit. (b) Carrier effective masses (dashed) and mobilities (solid) of polyyne as a function of strain: filled, electrons; hollow, holes.

Figure 4. Effect of end groups on carbyne BLA. Termination of the chain with sp3 groups (methyl CH3 and phenyl C6H5) increases the BLA, whereas the sp2 methylene group (CH2) decreases it, as compared to an unterminated infinite chain (black dashed line). The data for 12- and 100-atom chains show a weak decrease of BLA with chain length away from the ends with methylene termination.

Figure 2. Zero-point vibrations under strain. (left) Evolution of the vibrational structure of carbyne with strain. The ω -shaped lines show the potential energy as a function of BLA. Horizontal lines show the vibrational levels, and the shaded region is below the ZPV level. All quantities are normalized per 2-atom cell. (right) Real-space atomic density distributions based on ZPV wave functions (three one-atom unit cells shown, color indicates which part of the BLA wave function the density comes from).

C. R. Ma, J. Xiao and G. W. Yang Giant nonlinear optical responses of carbine//*J. Mater. Chem. C*, 2016, 4, 4692

Fig. 3 Formation of π -electron delocalization in carbyne. (A) Process of atomic orbital sp-hybridization. (B) Existence of extensive π -electron delocalization in carbyne.

Theresa Eder et al Switching between H- and J-type electronic coupling in single conjugated polymer aggregates//NATURE COMMUNICATIONS 8: 1641

Fig. 4 Pt spectra and PL decays of single chains and single aggregates. Normalized PL spectra, transient PL decays, and spectral PWHM values sortacted from the spectra in Fig. 3 and plotted in a histogram with 10 meV bins is the for single melecules a -ca and single aggregates 4 -f of PEB-1 (cep). PEB-2 (orange), and PEB-3 (green) in PMMA measured in air. Transient PL decays were fitted with an exponential plus an offset to account for the background, videring the PL littlemes stated in an 4 or e

Fig. 2 Switching between H-type and J-type coupling using solvent vapor annealing. a Schematic illustrating the splitting of single-spot PL with a dual-view unit into two detection channels, for photons with hv > 2.5 eV (denoted Igreen) and hv < 2.5 eV (denoted Ired), and imaging onto different areas on the same CCD camera. The fraction of red emission for each single spot is defined as Fred. b Accumulated wide-field dual-view fluorescence microscopy images of PPEB-1 aggregates of the same area from a 425 s movie during which the film conditions were changed. The first frame is accumulated during the first 50 s, the second frame at time 100-250 s and the last frame at 350-425 s. The z-scale is the same for all images. The first and the last frame are measured under ambient conditions and the central frame was obtained during SVA with a 1:4 ratio of toluene and hexane nitrogen vapor. Seven aggregates are marked with white circles. c Evolution of Fred values with 500 ms time resolution from the seven aggregates (gray curves) and their average (red/orange curve). d, e Normalized PL spectra and transient PL decays of a single aggregate in a dry (red) and swollen state (orange). The PL decays are fitted by a singleexponential function with an offset to extract the PL lifetime. f Histograms of the full width at half maximum (FWHM) of the PL spectra of 89 swollen PPEB-1 aggregates (orange) and 131 PPEB-1 molecules (blue) (all individual spectra are shown in Supplementary Fig. 1)

Curves on the plane

Topologies

Stabilities

Peano-curves (1D-strucures)

Fractal-curves (1D-strucures)

STABILITY OF LINEAR CARBON CHAINS

Tersoff potential

multivariable function interaction of neighboring atoms

$$\Phi_{n}(r_{n}) = \sum_{m \neq n}^{N} f_{c}(r_{nm})(f_{r}(r_{nm}) - a_{nm}f_{a}(r_{nm}))$$

$$m \neq n$$

$$attraction \qquad f_{r}(r_{nm}) = \varepsilon^{(1)} \exp\left(-\alpha r_{nm}\right)$$

$$a_{nm} = \left[1 + b_{n}^{\gamma}\left(\sum_{k \neq n,m} f_{c}(r_{nk})\omega_{nk}g(\varphi_{nmk})\right)^{\gamma_{n}}\right]^{-\frac{1}{2\gamma_{n}}}$$

$$g(\varphi_{nmk}) = 1 + \left(\frac{c_{n}}{d_{n}}\right)^{2} - \frac{c_{n}^{2}}{d_{n}^{2} + \left(e - \cos((\varphi_{nmk}))^{2}\right)}$$
repulsion
$$f_{a}(r_{nm}) = \varepsilon^{(2)} \exp\left(-\beta r_{nm}\right)$$

$$\varphi_{nm,k} - \text{angle between atoms n, m, and n, k}$$

$$structural function \qquad f_{c} = \left\{\frac{1}{2} + \frac{1}{2}\cos\left(\frac{\pi(r_{nm} + r^{(1)})}{\left(r^{(2)} + r^{(1)}\right)}\right), r^{(1)} < r_{nm} < r^{(2)}$$

$$(\Phi(r) \simeq 3 \times 10^{-16} - 26 \times 10^{-16} \text{V} \text{ for linear chains and form 2 till 20 atoms}$$

a

for linear chains для form 3 till 20 atoms Ψ(Γ) V

⇒
$$F(r) = -\frac{d\Phi(r)}{dr}$$
 F(r) ~ 10⁻⁴-10⁻⁶N

STM measurements on carbyne samples

(collaboration with Prof. Manuela Scarselli, Tor Vergata, Rome, Italy)

Scan size 400 nm x 400 nm (file name: m56)

LT NANOPROBE

2-probe spectroscopic measurements at atomic level

The future Carbyne laboratory

The International Center of Polaritonics invests in 1D crystals

- Very interesting new physics
- Applications in nano-electronics
- Applications in lasing and photonics
- Applications in quantum technologies
- SERS possibilities for biosensing and medicine

We do not want to repeat what Cambridge, Stanford and Tokyo do: we want to develop a new field and be the world leaders

Ultimate Nanoprobing at Low Temperatures

The Low Temperature NANOPROBE defines a new class of analytical instrumentation that merges SEM-navigated local transport measurements with atomic scale precision, high performance STM imaging, spectroscopy, and manipulation at LHe temperatures.

A major challenge in the development of novel devices in molecular and atomic scale electronics is their interconnection with larger scaled electrical circuits to control and characterize their functional properties. Local electrical probing by multiple probes with atomic precision can significantly improve efficiency in analysing electrical properties of individual structures without the need for full electrical integration. The LT NANOPROBE employs four independent, ultimate stability SPM's with precision in the picometer-range as individual probes for electrical transport measurements, and uses a scanning electron microscope for efficient and fast navigation of the probes.

The excellent stability allows for atomic resolution in STM and nc-AFM (QPlus) and expands applications towards the creation of atomically precise structures as well as their direct analysis by electrical transport measurements and SPM-based spectroscopy methods. The system - including simultaneous SPM and SEM operation - is operated near thermal equilibrium at T< SK and has been optimised towards extremely low thermal drift as the most important ingredient to allow for enough measurement time on atomic structures, a precision regime that is virtually inaccessible at room temperature.

Manipulation of a 4-Acetylbiphenyl (ABP) molecule [1,2] on Au(111), driven by inelastic tunneling effect. Data obtained during the TU Dresden team training session for the nanocar race at the PicoLab in Toulouse. Data by courtesy of F. Moresco, TU Dresden, Germany. References: [1] F. Moresco et al., ACS Nano, 7, 191 (2013); [2] F. Moresco et al., ACS Nano, 9, 8394 (2015)

LT NANOPROBE SEM Imaging and Tip Navigation at T< 5K

For the navigation of four independent STM probes, simultaneous SEM imaging is indispensable as it bridges dimensions from the mm-scale down to the nm-scale. The SEM enables a large field of view for probe coarse positioning as well as fine positioning and rapid localisation of nanometersized structures.

Sequence of SEM images taken at a sample temperature of T = 4.5 K. Probe navigation and positioning at the mm scale and high resolution imaging on Au islands on carbon with

The UHV Gemini column is the ultimate tool for that purpose. It offers unsurpassed resolution under true UHV conditions and at low temperatures.

In combination with the LT NANO-PROBE, the in-lens Secondary

Electron Detector (SED) represents a key advantage. Only one small access port is needed in the thermal shield compartment of the microscope stage (at T <5 K). Thus thermal impact is minimised, while still offering a suitable signal for high resolution imaging. **UHV** Gemini

column SEM

Alternatively, other UHV SEM columns or optical microscopes can cover the lower resolution range if sample structures do not require ultimate resolution.

typical size of 10-100nm. The SEM resolution with UHV Gemini column is specified to < 20nm using a 20/80 criteria (insert). Sub 10nm structures are visible.

ZnO nanowires with Au contacts characterised in the as-grown real device configuration using a local multi-probe method. Data courtesy: Steve P. Wilks et. al. / Nanotechnology 25 (2014) 425706

LT NANOPROBE STM for Probe Approach

STM is the key to advancing probing technology into the sub-nanometer scale. It ensures extremely accurate probe positioning and STM-based safe tip approach of fragile probe tips having diameters in the range of a few ten's of nanometers.

SEM ensures fast and efficient navigation of STM probes from the millimeter- to the nanometer-range. However, the STM tip shadows SEM imaging of structures smaller than the tip apex (please refer to page 10). Subsequently, STM is employed for atomically precise positioning of the tip and its point of contact.

Tip re-positioning accuracy is important as the probes are approached and positioned sequentially. During the approach process of an individual probe, the other probes need to be retracted to a safety distance of a few 100nm. When the positioning process is finished, all four probes are approached to contact. The outstanding precision of the LT Nanoprobe allows to land on the same atom again.

Sequence of STM images on Si(111) over 10 minutes with 200mm tip retraction in-between. Absolute lateral thermal drift X/Y = 33/30 pm in 10 minutes. Virtually identical line profiles show re-positioning accuracy at the atomic scale (blue and black curves show backward and forward scan, respectively).

Electrical Transport Measurements

During STM approach the distance control is based on tunnelling current feedback and therefore requires a dedicated low noise I/V converter. When the tunnelling contact is established, the individual probe-sample distance is well controlled in the nm range.

To establish electrical contact and to control its resistance, the STM feedback is de-activated and the probe is manually approached by setting a piezo scanner z-offset. The individual contact properties are analysed by an IV measurement between the tip and the grounded sample.

Transport measurements in various configurations such as four-point transport or three terminal measurements with one tip acting as (tunnelling) gate, require the I/V converter to be taken out of the signal line. Thus, a pA STM compatible and TTL trigger controlled switching technology is used to route signals of the four probes to external BNC connectors. Using LabVIEW, experimental workflows can be integrated with third party measurement electronics.

Schematic showing the function principle of signal re-routing from the probe tip either to the I/V converter for STM feedback to the MATRIX control system or to a BNC connector to connect external electronics.

Carbon perspectives

SCIENTIFIC REPORTS

OPEN Nanocrystalline hexagonal diamond formed from glassy carbon

Received: 03 August 2016 Accepted: 26 October 2016 Published: 29 November 2016

Thomas. B. Shiell¹, Dougal G. McCulloch², Jodie E. Bradby¹, Bianca Haberl³, Reinhard Boehler⁴ & David. R. McKenzie⁵

SCIENTIFIC REPORTS

OPEN The Nature of Metastable AA' Graphite: Low Dimensional Nanoand Single-Crystalline Forms

Received: 21 October 2016 Accepted: 23 November 2016 Sublished, 31 December 3016

Jae-Kap Lee¹, Jin-Gyu Kim², K. P. S. S. Hembram¹, Yong-II Kim³, Bong-Ki Min⁴, Yeseul Park^{1,5}, Jeon-Kook Lee¹, Dong Ju Moon⁶, Wooyoung Lee⁵, Sang-Gil Lee² & Phillip John⁷

Carbon 136 (2018) 337344										
	Contents lists available at ScienceDirect	Carbon								
	Carbon	7000								
ELSEVIER	journal homepage: www.elsevier.com/locate/carbon									

Deyse G. Costa a, b, **, Fábio J.F.S. Henrique ^c, Felipe L. Oliveira ^c, Rodrigo B. Capaz ^{b, ***}, Pierre M. Esteves ^{c,*}

n-Diamondynes: Expanding the family of carbon allotropes

	Contents lists available at ScienceDirect	Carbon
5-52 E.	Carbon	
ELSEVIED	iournal homepage: www.elsevier.com/locate/carbon	Land Control C

Carbon 132 (2018) 785-801

Perspectives

nature materials

A carbon science perspective in 2018: Current achievements and future challenges

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Alberto Bianco^a, Yongsheng Chen^b, Yuan Chen^c, Debjit Ghoshal^d, Robert H. Hurt^e, Yoong Ahm Kim^{f, g}, Nikhil Koratkar^{h, i}, Vincent Meunier^j, Mauricio Terrones^{k, l, m, n, o, p, *}

	-	~	-		-	~			-	-	10		-
- к	E	s	E	А	к	c	н	Α	к		IC	L	E

MATERIALS

Carbyne with finite length: The one-dimensional sp carbon

2015 © The Authors, some rights res exclusive licensee American Associati the Advancement of Science, Distrib under a Creative Commons Attributi NonCommercial License 4.0 (CC BY-I 10.1126/sdady.1500857

Bitao Pan,* Jun Xiao,* Jiling Li,* Pu Liu, Chengxin Wang, Guowei Yang[†]

Confined linear carbon chains as a route to bulk carbyne

Lei Shi¹, Philip Rohringer¹, Kazu Suenaga², Yoshiko Niimi², Jani Kotakoski¹, Jannik C. Meyer¹, Herwig Peterlik¹, Marius Wanko³, Seymur Cahangirov^{3,4}, Angel Rubio^{3,5}, Zachary J. Lapin⁶, Lukas Novotny⁶, Paola Ayala^{1,7} and Thomas Pichler^{1*}