1st International Workshop
on

Nano-scale Spectroscopy and its Applications to Semiconductor Research

December 11 - 14, 2000
Trieste, Italy

PHYSICAL REVIEW B 77, 104425 (2008)

Experimental investigation of the spin reorientation of Co/Au based magnetic nanodot arrays

L. Gridneva,[1,*] A. Persson,[1] M. Á. Niño,[2,†] J. Camarero,[2] J. J. de Miguel,[2] R. Miranda,[2,3] C. Hofer,[4] C. Teichert,[4] T. Bobek,[5] A. Locatelli,[6] S. Heun,[7] S. Carlsson,[8] and D. Arvanitis[1]

SEVIER Journal of Electron Spectroscopy and Related Phenomena 144–147 (2005) 1163–1166

www.elsevier.com/locate/elsp

LEEM and XPEEM studies of C-AFM induced surface modifications of thermally grown SiO_2

S. Heun[a,*], S. Kremmer[b], D. Ercolani[a,c], H. Wurmbauer[b], C. Teichert[b]

APPLIED PHYSICS LETTERS 87, 223106 (2005)

Surface compositional gradients of InAs/GaAs quantum dots

G. Biasiol[a)] and S. Heun
Laboratorio Nazionale TASC INFM-CNR, I-34012 Trieste, Italy

G. B. Golinelli
Università degli Studi di Modena e Reggio Emilia, I-41100 Modena, Italy

A. Locatelli and T. O. Mentes
Sincrotrone Trieste S.c.p.a., I-34012 Trieste, Italy

F. Z. Guo
JASRI/SPring-8, 1-1-1, Kouto, Mikazuki, Sayo, Hyogo 679-5198, Japan

C. Hofer and C. Teichert
Institute of Physics, Montanuniversität Leoben—University of Leoben, A-8700 Leoben-Austria

L. Sorba
Laboratorio Nazionale TASC INFM-CNR, I-34012 Trieste, Italy, and Università degli Studi di Modena e Reggio Emilia, I-41100 Modena, Italy

PHYSICAL REVIEW B 71, 214422 (2005)

Imaging of magnetic nanodots on self-organized semiconductor substrates

A. M. Mulders,* A. Fraile Rodríguez,* and D. Arvanitis
Department of Physics, Uppsala University, Box 530, S-75121 Uppsala, Sweden

C. Hofer and C. Teichert
Institut für Physik, Montanuniversität Leoben, Franz Josef Str. 18, A-8700 Leoben, Austria

M. Á. Niño, J. Camarero, J. J. de Miguel, and R. Miranda
Departamento de Física de la Materia Condensada and Instituto de Física de Materiales "Nicolás Cabrera" Universidad Autónoma de Madrid, Cantoblanco, 28049 Madrid, Spain

K. Lyutovich and E. Kasper
Institut für Halbleitertechnik, Universität Stuttgart, Pfaffenwaldring 47, 70569 Stuttgart, Germany

S. Heun† and A. Locatelli
Sincrotrone Trieste, S.S. 14, km 163.5, 34012 Basovizza (TS), Italy
(Received 22 December 2004; published 24 June 2005)

JOURNAL OF APPLIED PHYSICS 97, 104333 (2005)

Behavior of SiO_2 nanostructures under intense extreme ultraviolet illumination

S. Heun[a)]
Laboratorio Tecnologie Avanzate e nanoSCienze-Istituto Nazionale per la Fisica della Materia (TASC-INFM), Area di Ricerca, I-34012 Bassovizza (Trieste), Italy

S. Kremmer
Institute of Physics, University of Leoben, A-8700 Leoben, Austria

D. Ercolani
Laboratorio Tecnologie Avanzate e nanoSCienze-Istituto Nazionale per la Fisica della Materia (TASC-INFM), Area di Ricerca, I-34012 Basovizza (Trieste), Italy and Università degli Studi di Modena e Reggio Emilia, Via Campi 213/A, I-41100 Modena, Italy

H. Wurmbauer and C. Teichert
Institute of Physics, University of Leoben, A-8700 Leoben, Austria

Black Phosphorus n-type doping by Cu: a microscopic surface investigation

Stefan Heun

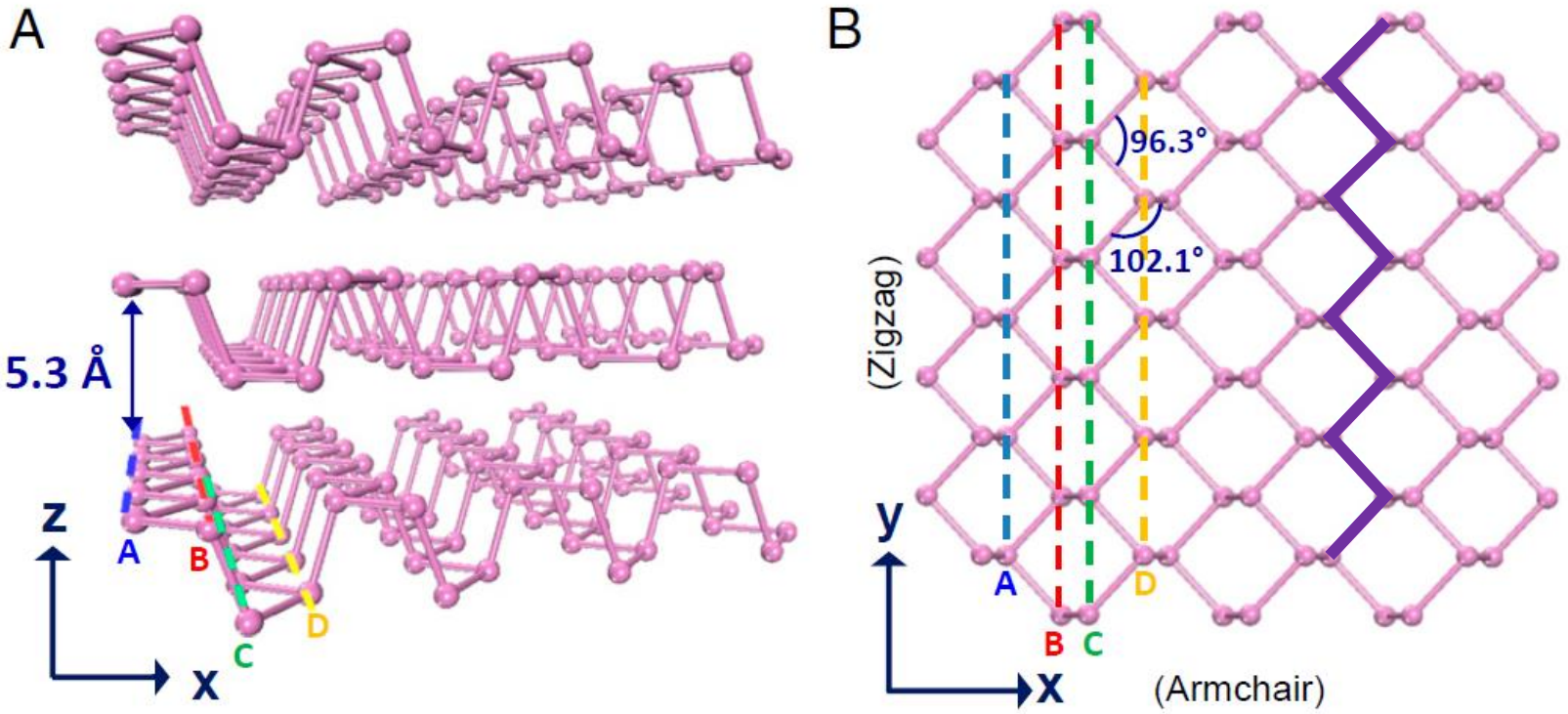
NEST, Istituto Nanoscienze-CNR and Scuola Normale Superiore, Piazza San Silvestro, Pisa, Italy

National Enterprise for nanoScience and nanoTechnology

NEST

Black phosphorus (bP)

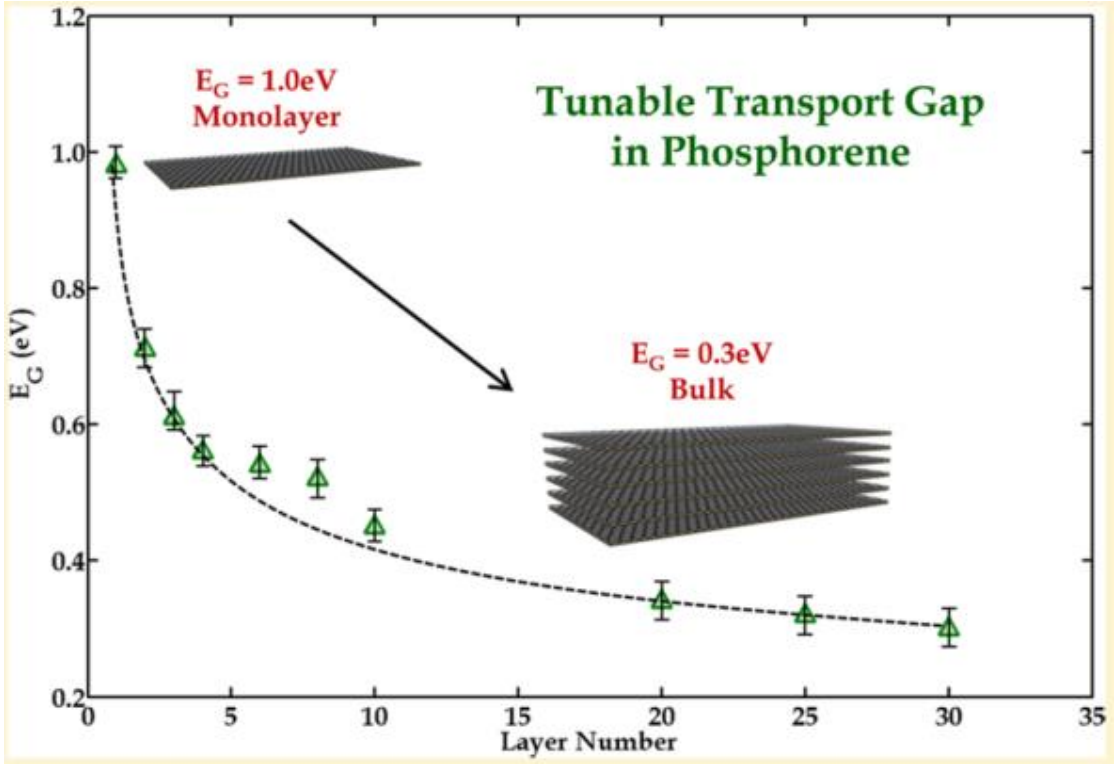
- Black Phosphorus is a layered van der Waals crystal with a puckered structure



X. Ling et al., PNAS 112 (2015) 4523.

Black phosphorus (bP)

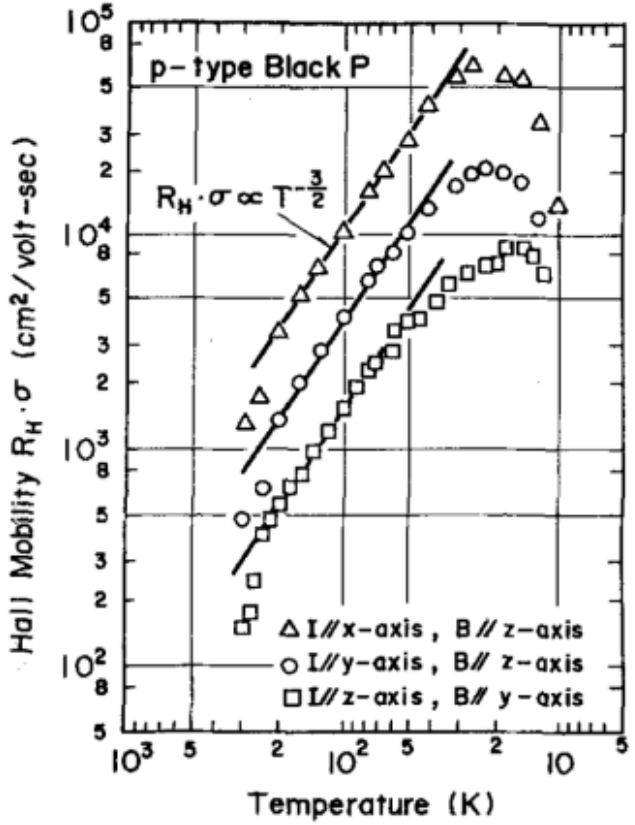
- Black Phosphorus is a layered van der Waals crystal with a puckered structure
- Direct band gap which ranges from 0.3 eV (bulk) to ~2.0 eV (monolayer)



S. Das et al., Nano Letters 14 (2014) 5733.

Black phosphorus (bP)

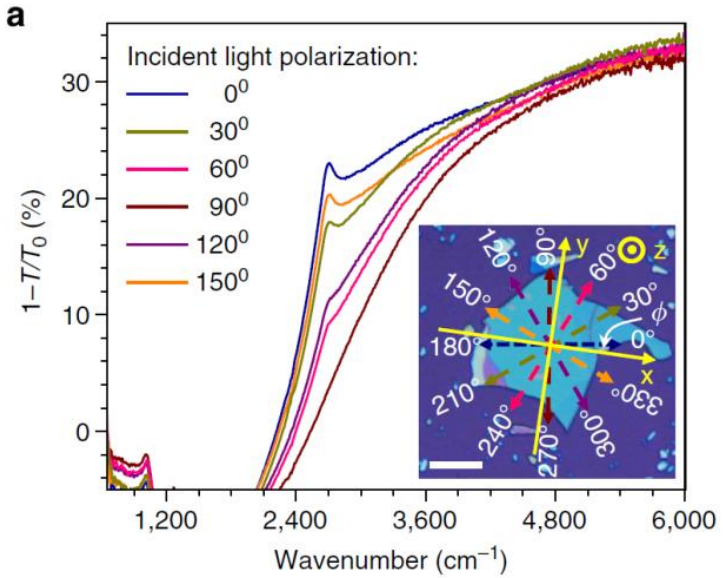
- Black Phosphorus is a layered van der Waals crystal with a puckered structure
- Direct band gap which ranges from 0.3 eV (bulk) to ~2.0 eV (monolayer)
- High carrier mobility

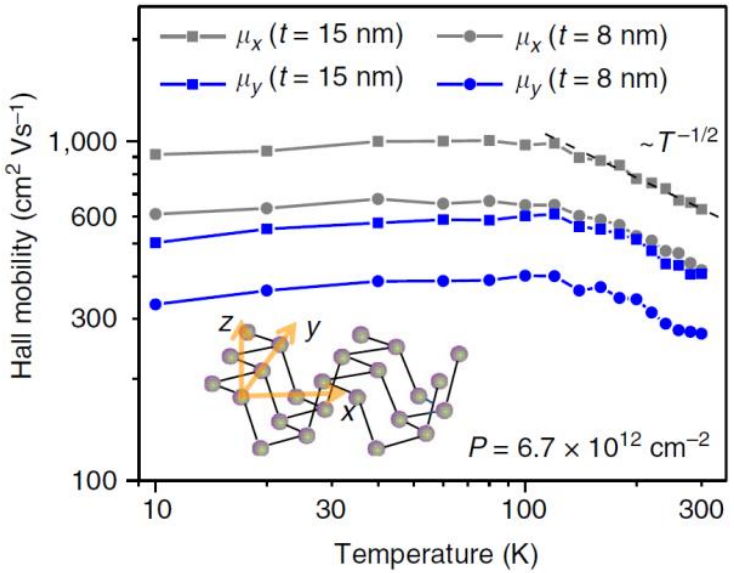


A. Morita, Appl. Phys. A 39 (1986) 227.

Black phosphorus (bP)

- Black Phosphorus is a layered van der Waals crystal with a puckered structure
- Direct band gap which ranges from 0.3 eV (bulk) to ~2.0 eV (monolayer)
- High carrier mobility
- In-plane anisotropy of its optical and transport properties

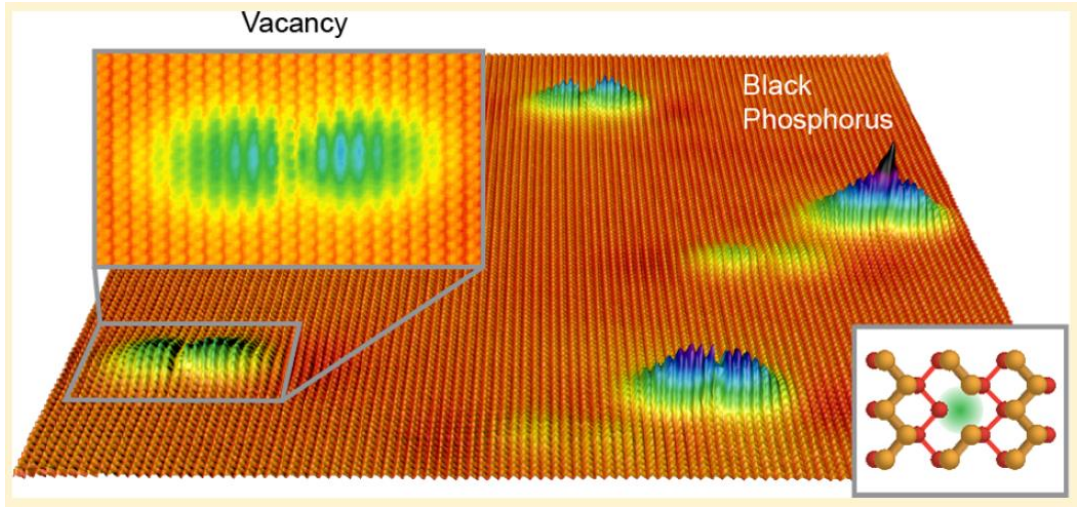




F. Xia et al., Nat. Commun. 5 (2014) 4458.

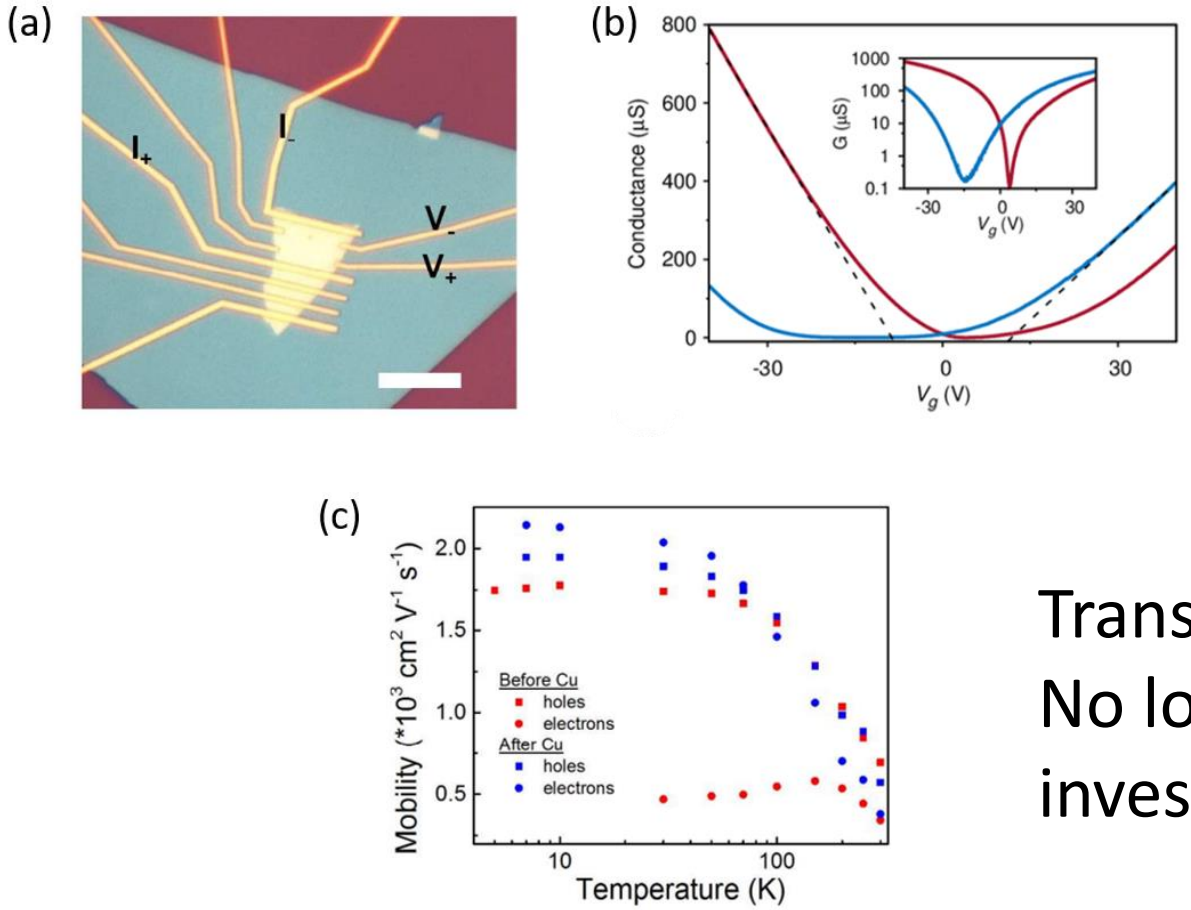
Black phosphorus (bP)

- Black Phosphorus is a layered van der Waals crystal with a puckered structure
- Direct band gap which ranges from 0.3 eV (bulk) to ~2.0 eV (monolayer)
- High carrier mobility
- In-plane anisotropy of its optical and transport properties
- Intrinsic p-type semiconductor due to P vacancies



B. Kiraly et al., Nano Letters 17 (2017) 3607.

n-type doping of bP by Cu



Transport Study;
No local spectroscopic investigation so far

S. P. Koenig et al., Nano Letters, 2016, 16, 2145.

IOP Publishing 2D Mater. 6 (2019) 015005 https://doi.org/10.1088/2053-1583/aadd20

2D Materials

OPEN ACCESS

PAPER

STM study of exfoliated few layer black phosphorus annealed in ultrahigh vacuum

RECEIVED
1 June 2018

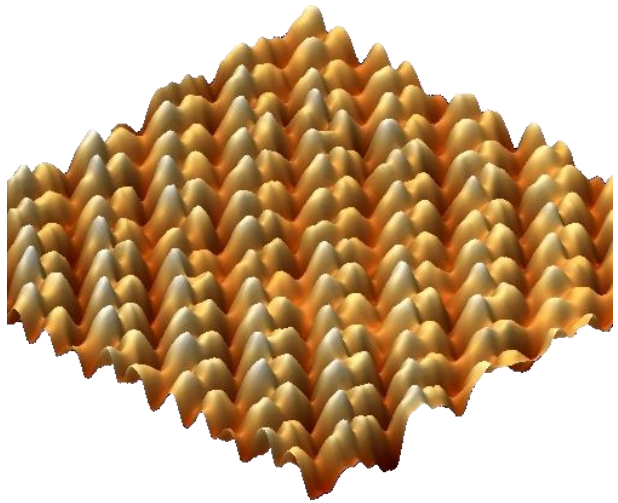
REVISED
20 August 2018

ACCEPTED FOR PUBLICATION
28 August 2018

PUBLISHED
22 October 2018

Abhishek Kumar[1], F Telesio[1], S Forti[2], A Al-Temimy[2], C Coletti[2], M Serrano-Ruiz[3], M Caporali[3], M Peruzzini[3], F Beltram[1] and S Heun[1]

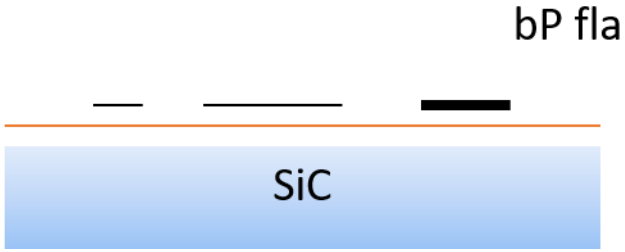
[1] NEST, Istituto Nanoscienze-CNR and Scuola Normale Superiore, Piazza San Silvestro 12, 56127 Pisa, Italy
[2] Center for Nanotechnology Innovation @ NEST, Istituto Italiano di Tecnologia, Piazza San Silvestro 12, 56127 Pisa, Italy
[3] CNR-ICCOM, Via Madonna del Piano 10, 50019 Sesto Fiorentino, Italy



A. Kumar et al., 2D Materials 6 (2019) 015005.

Glove Bag Exfoliation

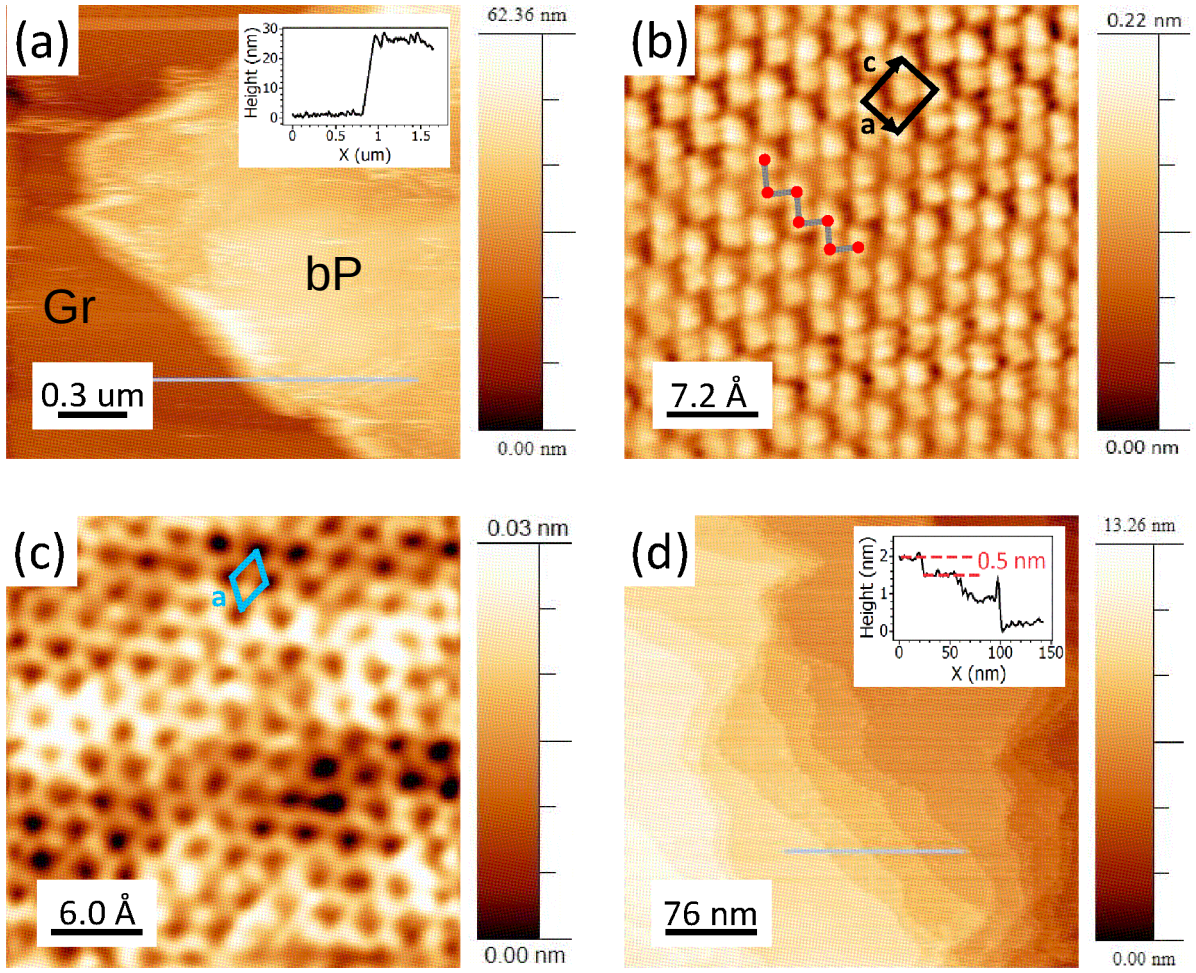
- MLG on SiC – conducting substrate for STM
- Inert atmosphere exfoliation
- Exfoliation, transfer, mounting and transportation to STM chamber – all inside N_2 atmosphere
- Loadlock (STM) also flushed with N_2
- Exposed to air for few seconds only



A. Kumar et al., 2D Materials 6 (2019) 015005.

STM of pristine bP exfoliated on graphene

h ~ 25 nm

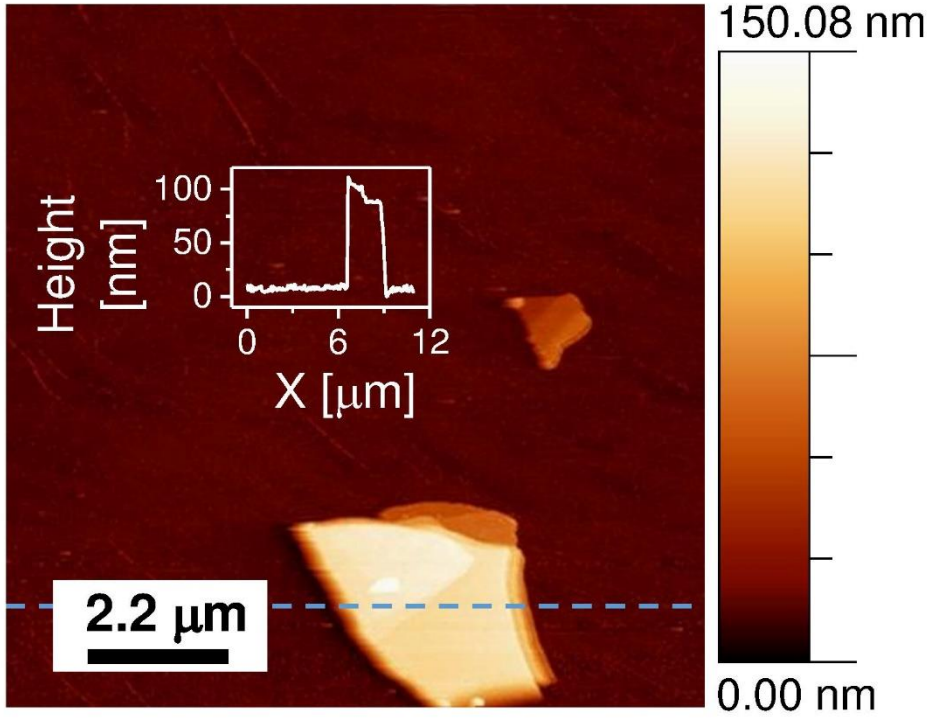


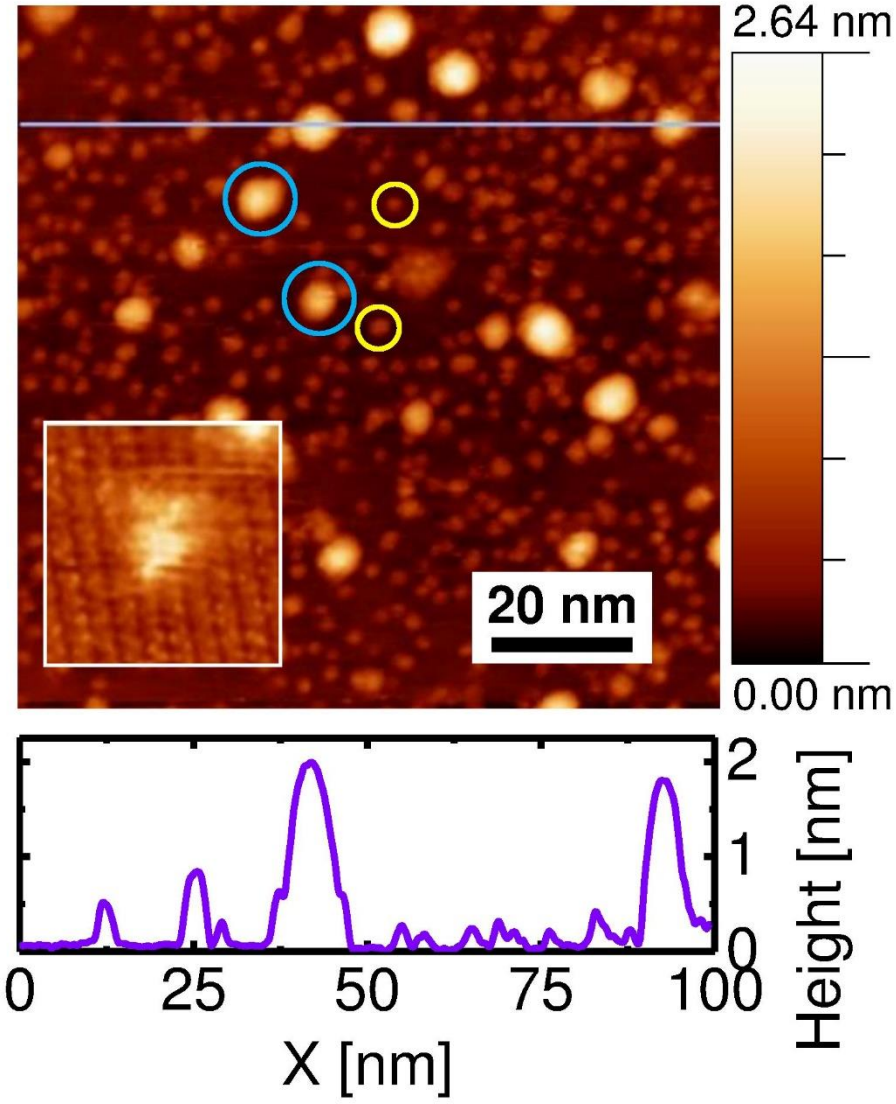
a = 3.45 Å
c = 4.40 Å

A. Kumar et al., 2D Materials 6 (2019) 015005.

STM: 0.8 ML Cu on bP

Cu grows in Volmer-Weber mode

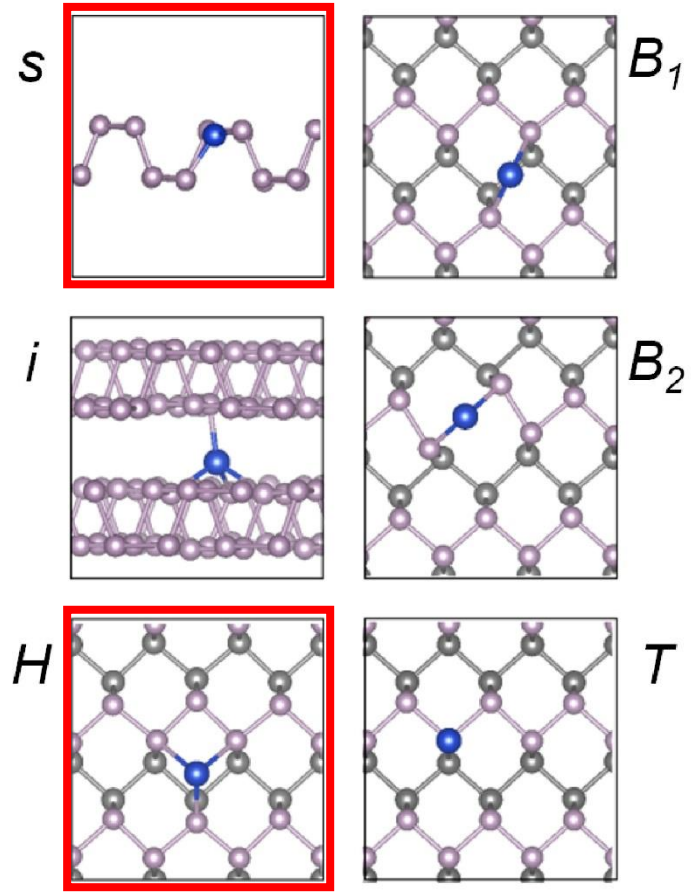




Atomic resolution of bP after copper deposition demonstrates the high quality of copper-deposited bP sample

A. Kumar et al., J. Phys. Chem. C 125 (2021) 13477.

DFT: Cu on bP



s: substitutional

B1: bridge

i: interstitial

B2: bridge

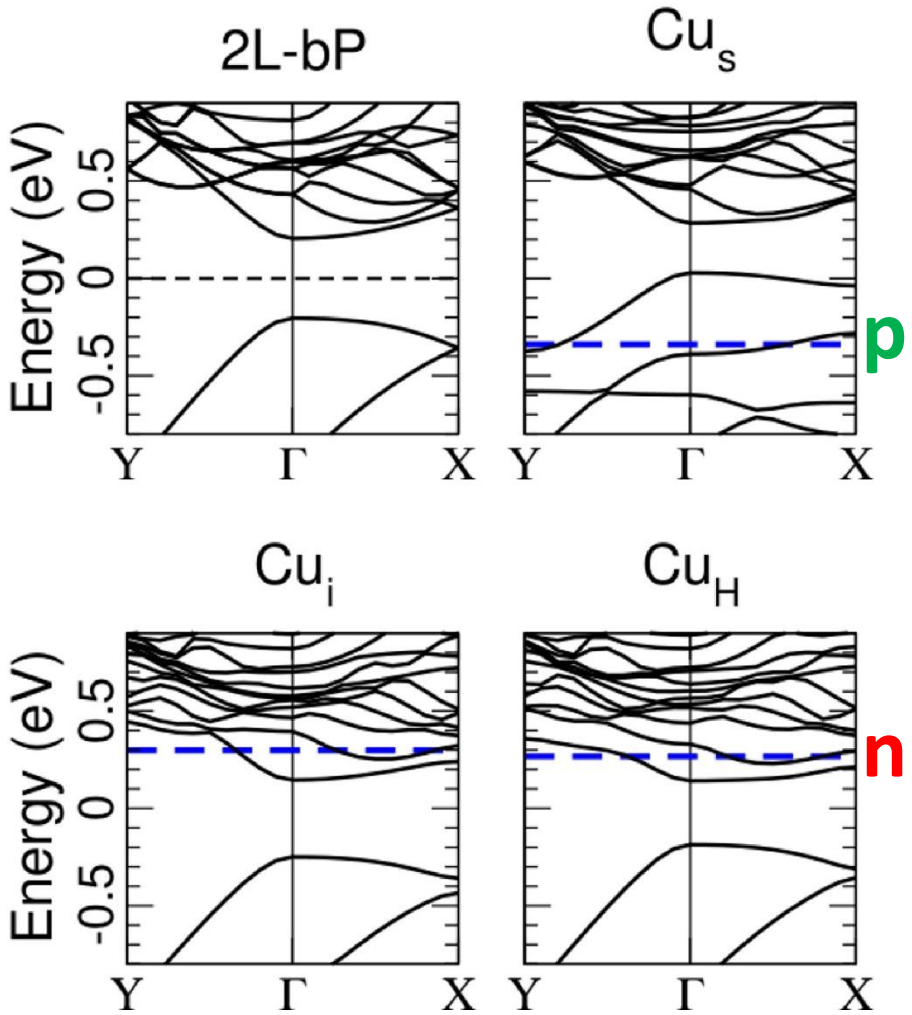
H: hollow

T: top

- Cluster formation is always favored, in overall agreement with experimental observations.
- Cluster nucleation around Cu_s sites is the (thermodynamically) most favorable process.

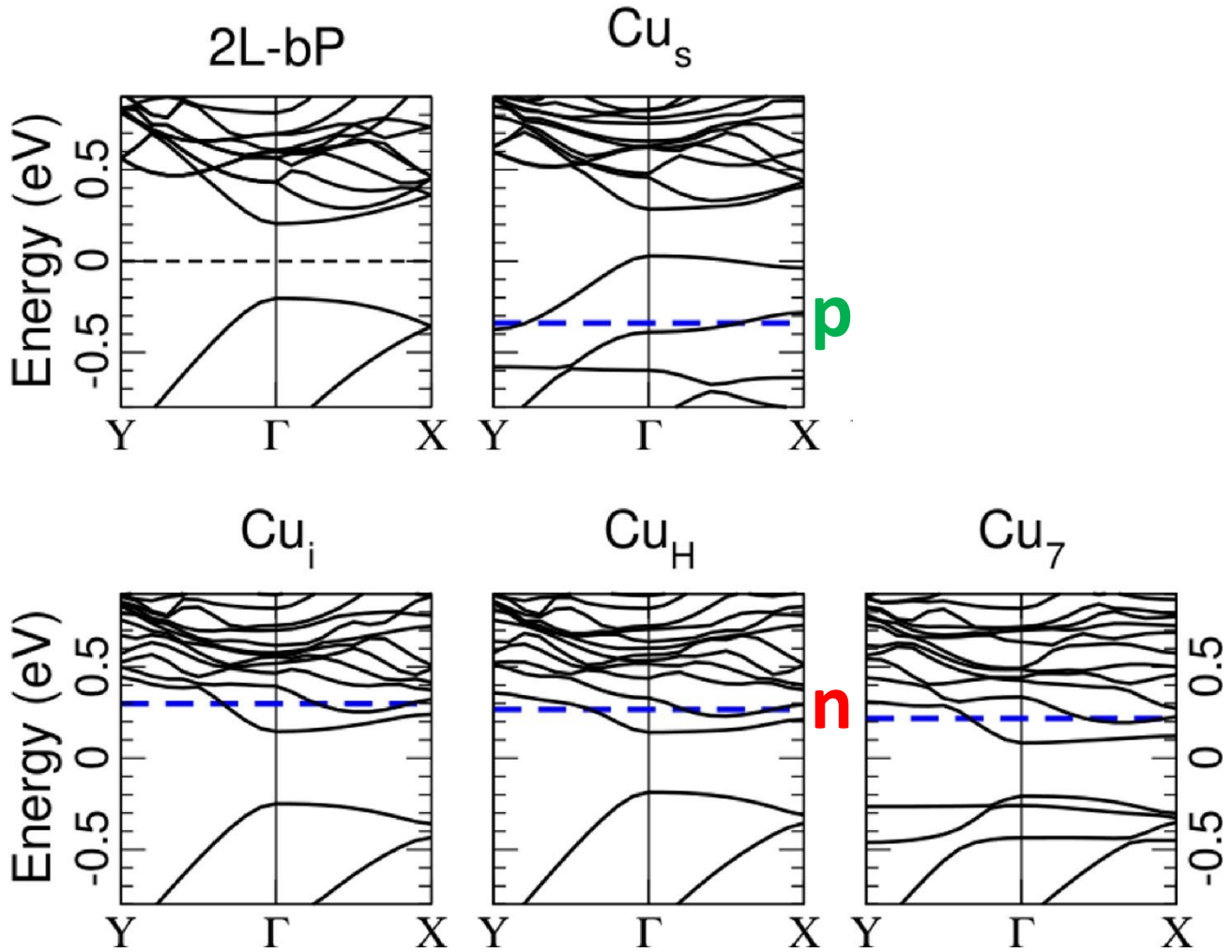
A. Kumar et al., J. Phys. Chem. C 125 (2021) 13477.

DFT: Cu on bP



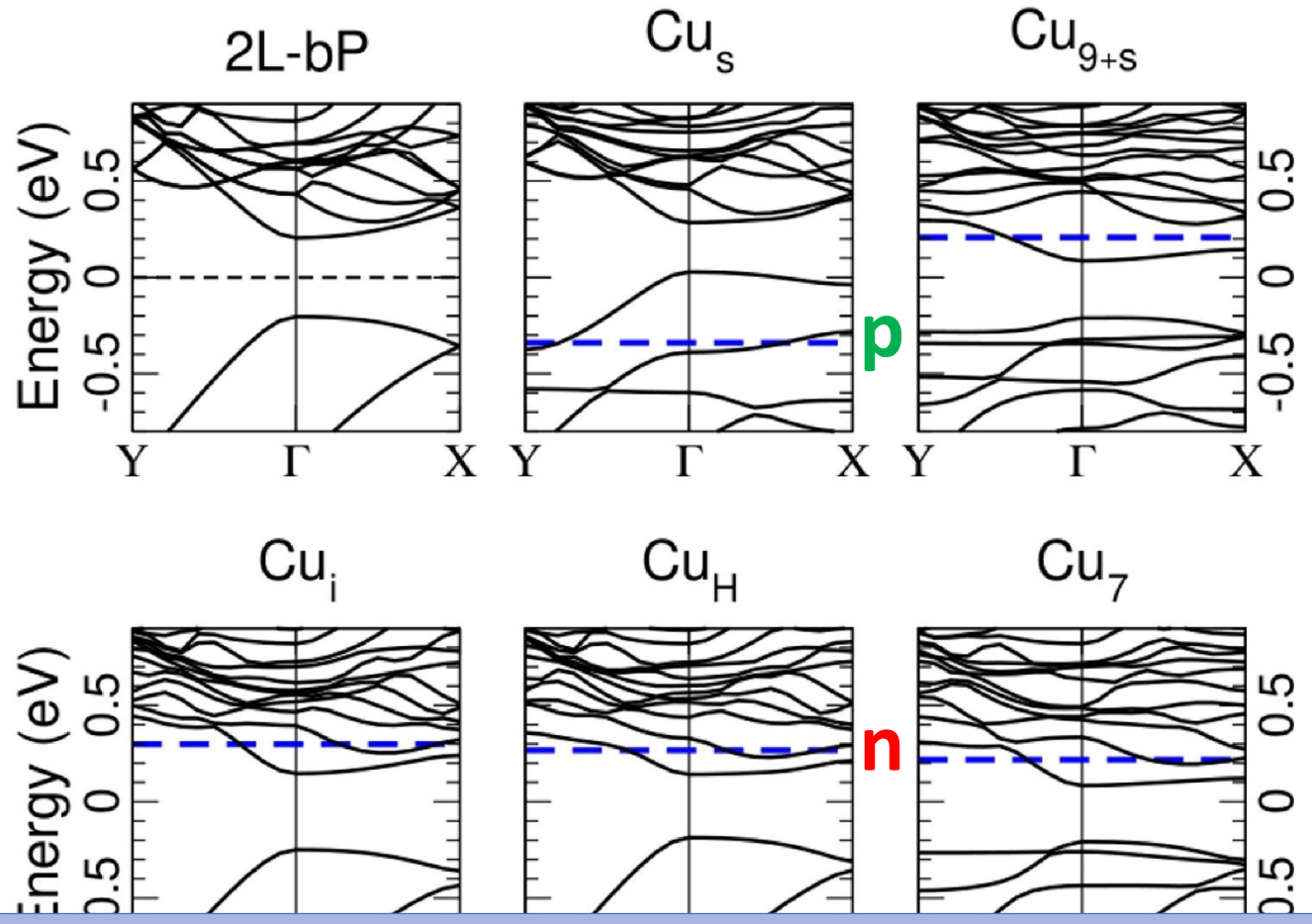
A. Kumar et al., J. Phys. Chem. C 125 (2021) 13477.

DFT: Cu on bP



A. Kumar et al., J. Phys. Chem. C 125 (2021) 13477.

DFT: Cu on bP

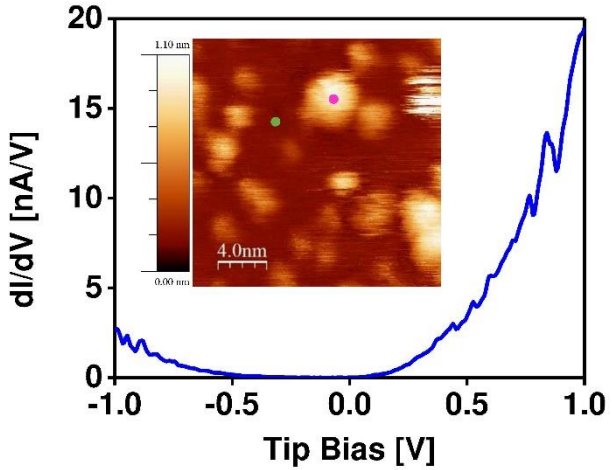


Band gap reduction in presence of Cu atoms

A. Kumar et al., J. Phys. Chem. C 125 (2021) 13477.

STS: bP and Cu

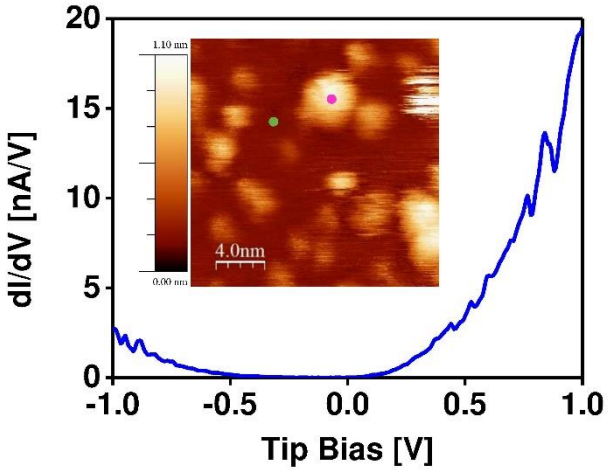
pristine bP



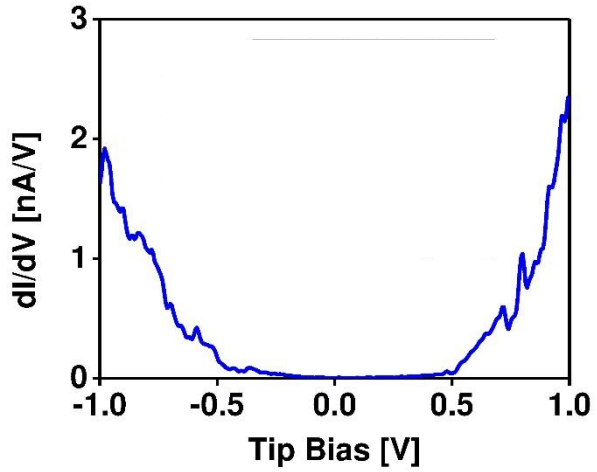
A. Kumar et al., J. Phys. Chem. C 125 (2021) 13477.

STS: bP and Cu

pristine bP



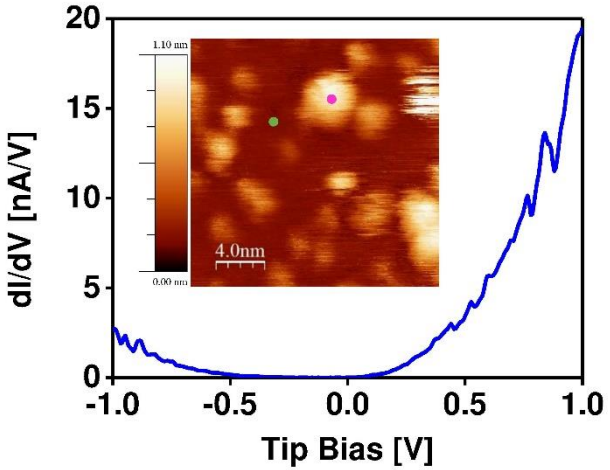
Cu on bP

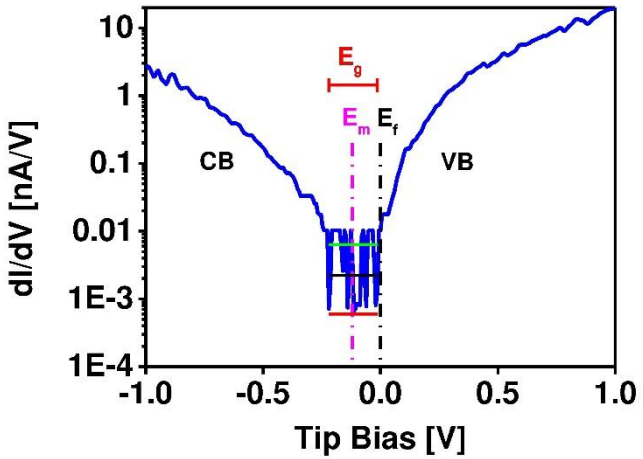


A. Kumar et al., J. Phys. Chem. C 125 (2021) 13477.

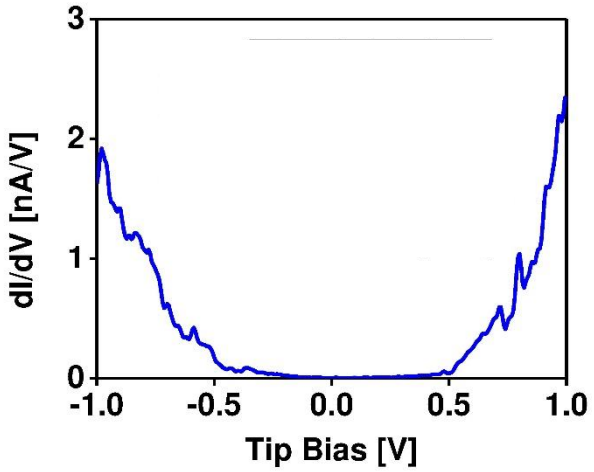
STS: bP and Cu

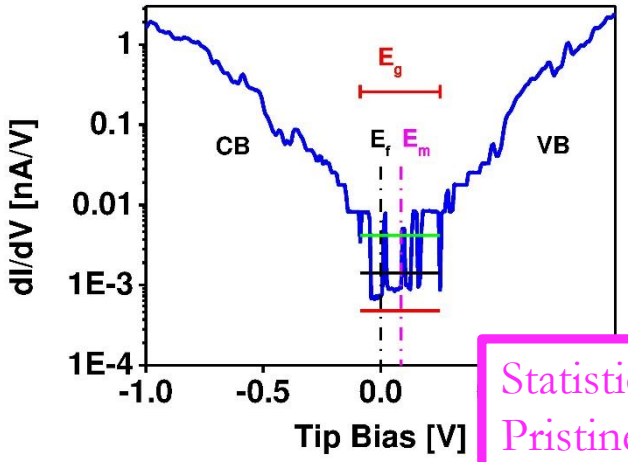
pristine bP





Cu on bP

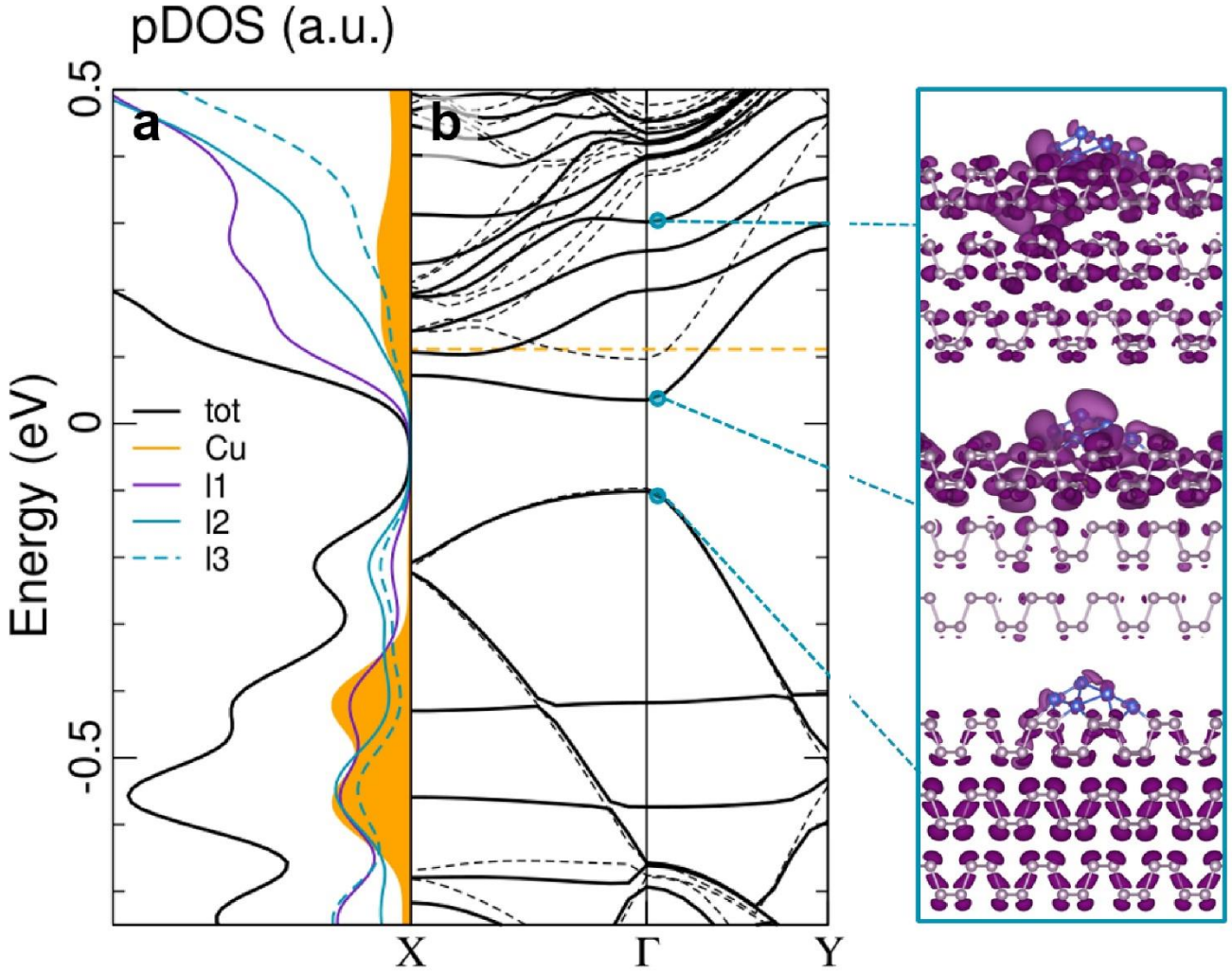


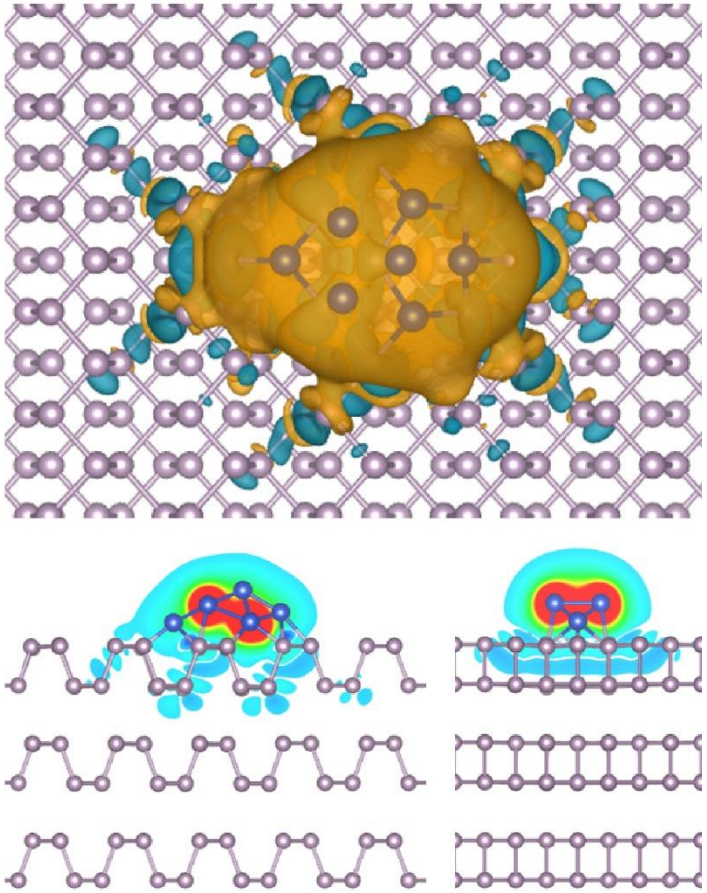


Statistical analysis of 42 spectra
Pristine bP → (0.25 ± 0.10) eV
Cu-Doped bP → (0.46 ± 0.20) eV

A. Kumar et al., J. Phys. Chem. C 125 (2021) 13477.

DFT: Cu_7 on bP

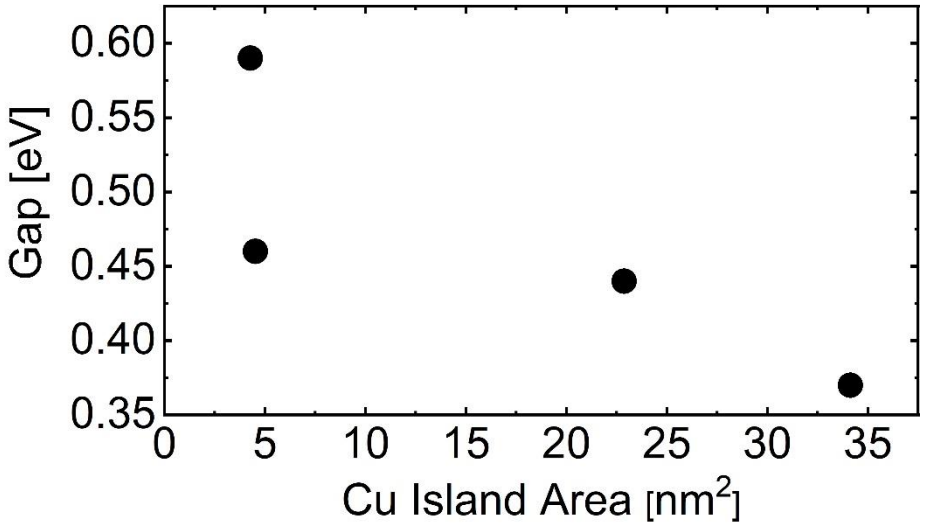




A. Kumar et al., J. Phys. Chem. C 125 (2021) 13477.

Coulomb blockade

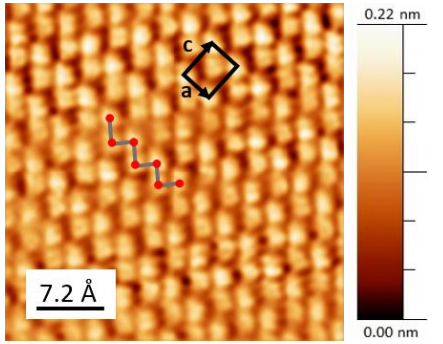
- Gap increase can be understood invoking Coulomb blockade of the Cu islands
- Parallel plate capacitor model: $C \approx 10^{-18}$ F → charging energy 100 meV
- Experimentally observed gap = Coulomb gap

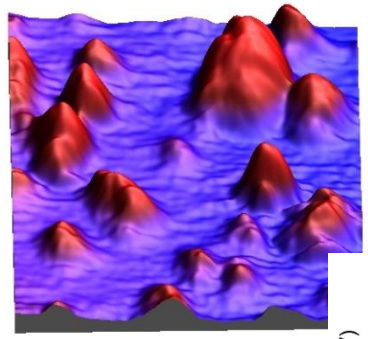


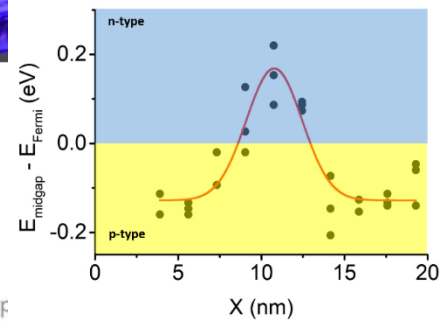
A. Kumar et al., J. Phys. Chem. C 125 (2021) 13477.

Summary

- Developed an innovative method that allows to perform STM on exfoliated clean nanometer thin bP surfaces
- Can be applied to other air-sensitive 2D materials also
- Studied surface morphology and doping effects of copper on bP
- Can be used to make high performance p-n junctions







National Enterp

People Involved

Theory

Abhishek Kumar

Francesca Telesio

Deborah Prezzi

Claudia Cardoso

Alessandra Catellani

Graphene

Stiven Forti

Camilla Coletti

bP

Manuel Serrano-Ruiz

Maurizio Peruzzini

National Enterprise for nanoScience and nanoTechnology

CNRNANO PISA NEST

Thank you for your attention!

National Enterprise for nanoScience and nanoTechnology

NEST