Optimization of few-layer black phosphorus for low-temperature magneto-transport studies

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Black phosphorus

Layered structure with orthorhombic symmetry

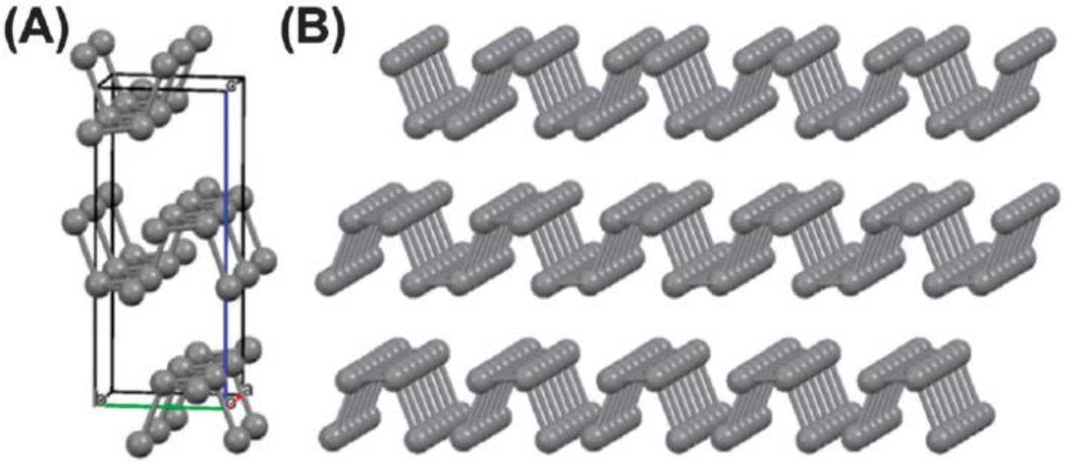


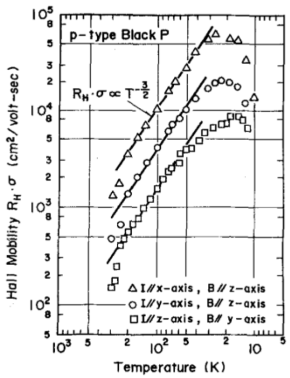
Fig. 1 The chemical structures of the compounds in this study. (A) The orthorhombic unit cell of black phosphorus[19] (a = 3.31 Å, b = 4.38 Å c = 10.50 Å, $\alpha = \beta = \gamma = 90°$; space group *Bmab*; Crystallography Open Database ID: 1010325) which generates a layer structure comprising corrugated lamellae of phosphorus atoms held together by weak interlayer forces. (B) Three-layer phosphorene.

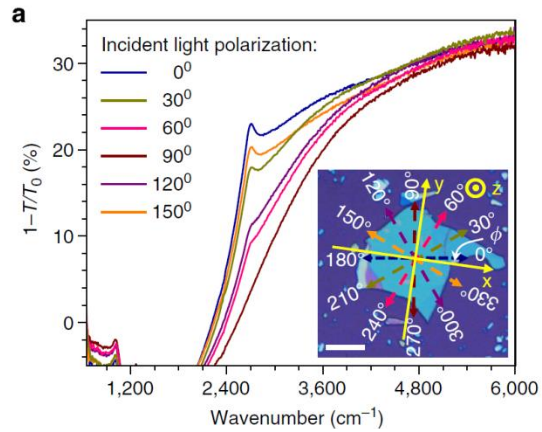
Cell parameters
a=3.13Å
b=10.47Å
c=4.37Å

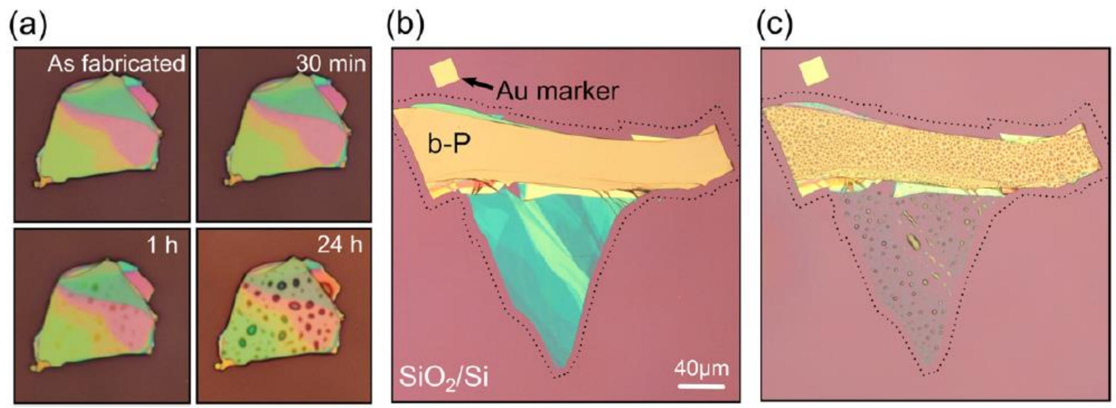
J. R. Brent et al., Chem. Commun. 50 (2014) 13338.

The renaissance of black phosphorus

- In 1914 first successful synthesis (Bridgman) and in 2007 synthesis at room pressure (Lange, Nilges)
- p-type semiconductor: 0.3eV direct band gap and high hole mobility (64,000 cm²/Vs @ 20 K)
- 1983 (Narita): n-type doping by Te
- 2014: First publications on bP layered thin films
- Highly reactive in air
- Band-gap tunable with layer number
- **In-plane anisotropy** of optical and transport properties



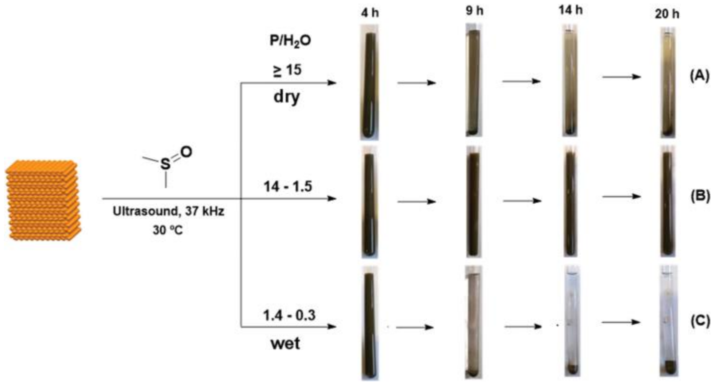




A. Morita, Appl. Phys. A 39 (1986) 227, S. Das et al., Nano Lett. 14 (2014) 5733,
F. Xia et al., Nat. Comm. 5 (2014) 4458,
A. Castellanos-Gomez et al., 2D Mater. 1 (2014) 025001

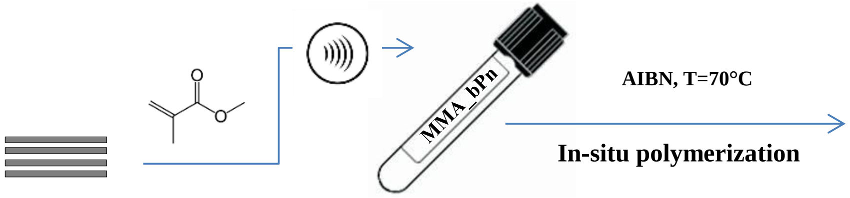
bP exfoliation

- Liquid exfoliation of bP in dimethylsulfoxide (DMSO)



Adv. Mater. Interfaces **2016**, *3*, 1500441

- Direct exfoliation in a polymer matrix



PMMA/bP hybrid material

Chem. Mater., DOI: 10.1021/acs.chemmater.7b05298

- Mechanical exfoliation

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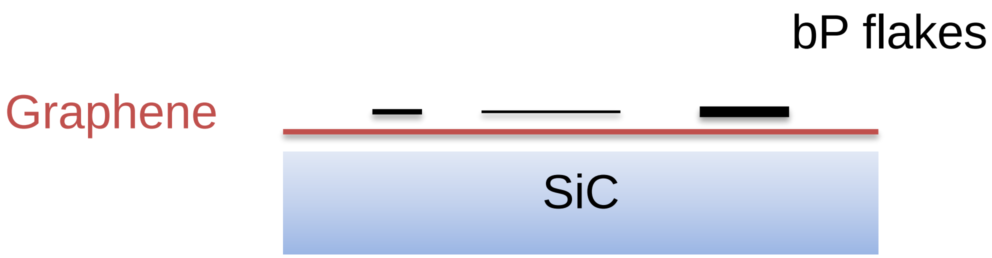
bP flake surface science



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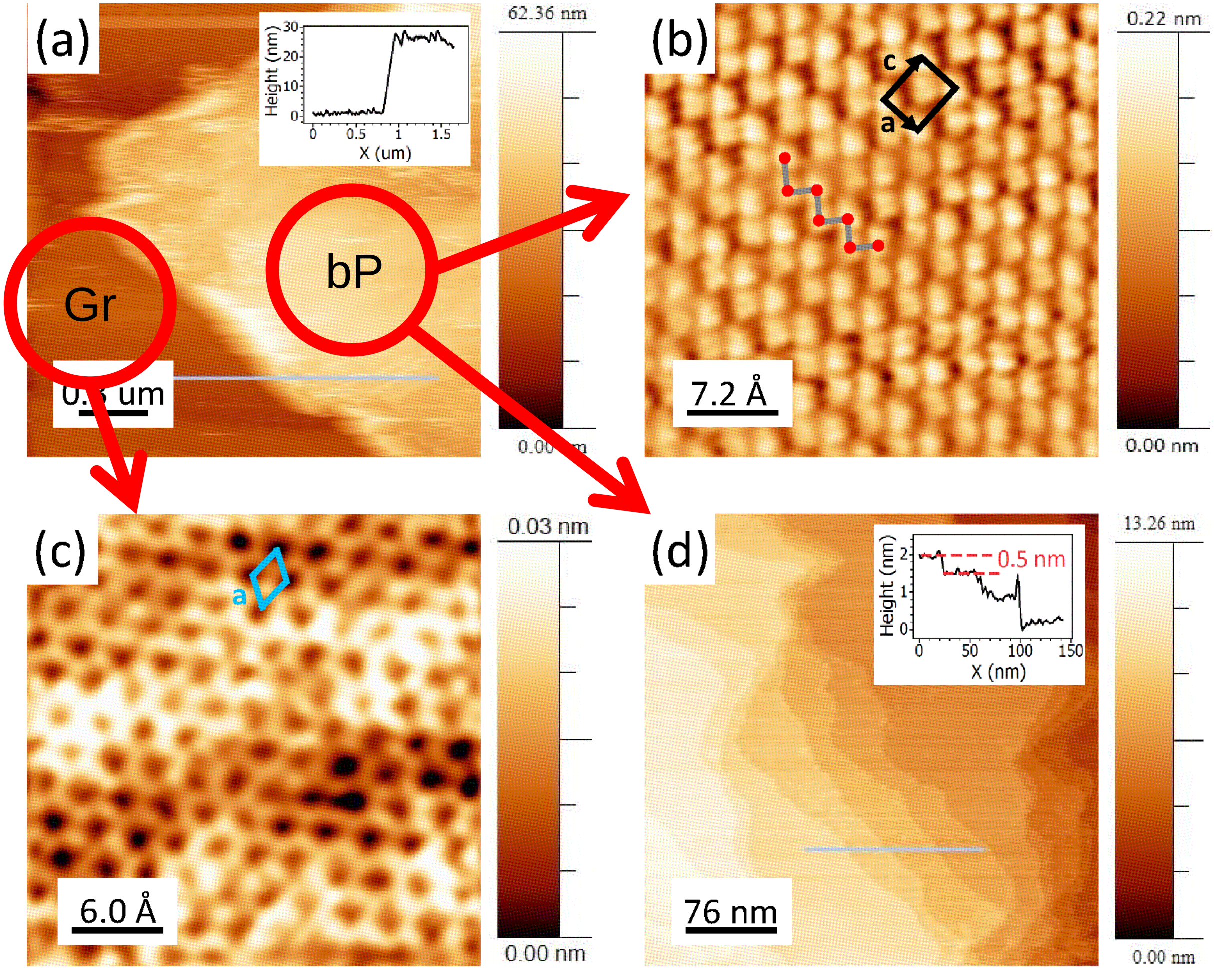
STM imaging of bP flakes exfoliated on graphene

h ~ 25 nm



a = 3.45 Å
c = 4.40 Å

Abhishek Kumar et al., J. Phys. Chem. C, submitted.

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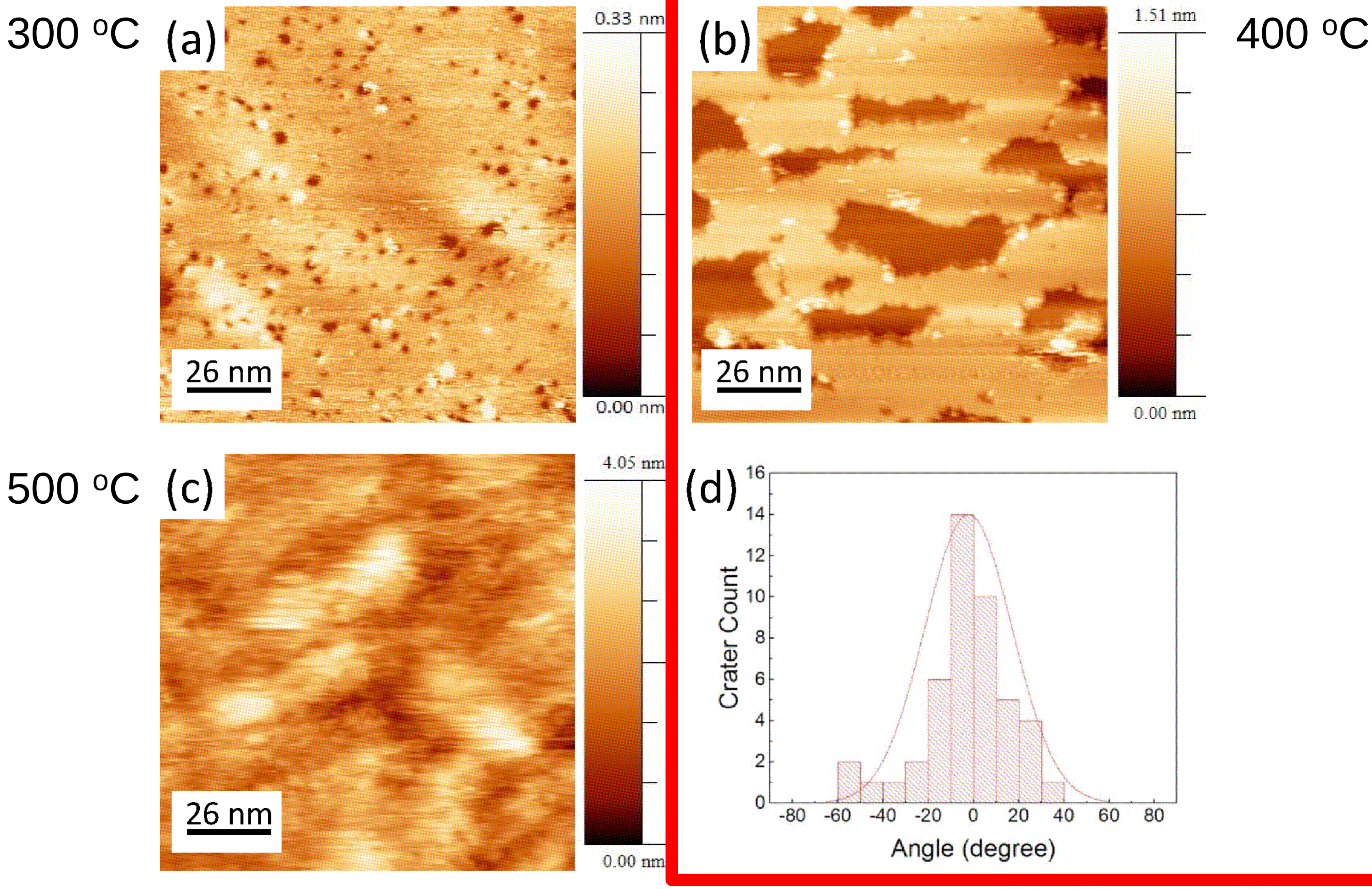
bP annealing



Abhishek Kumar et al., J. Phys. Chem. C, submitted.

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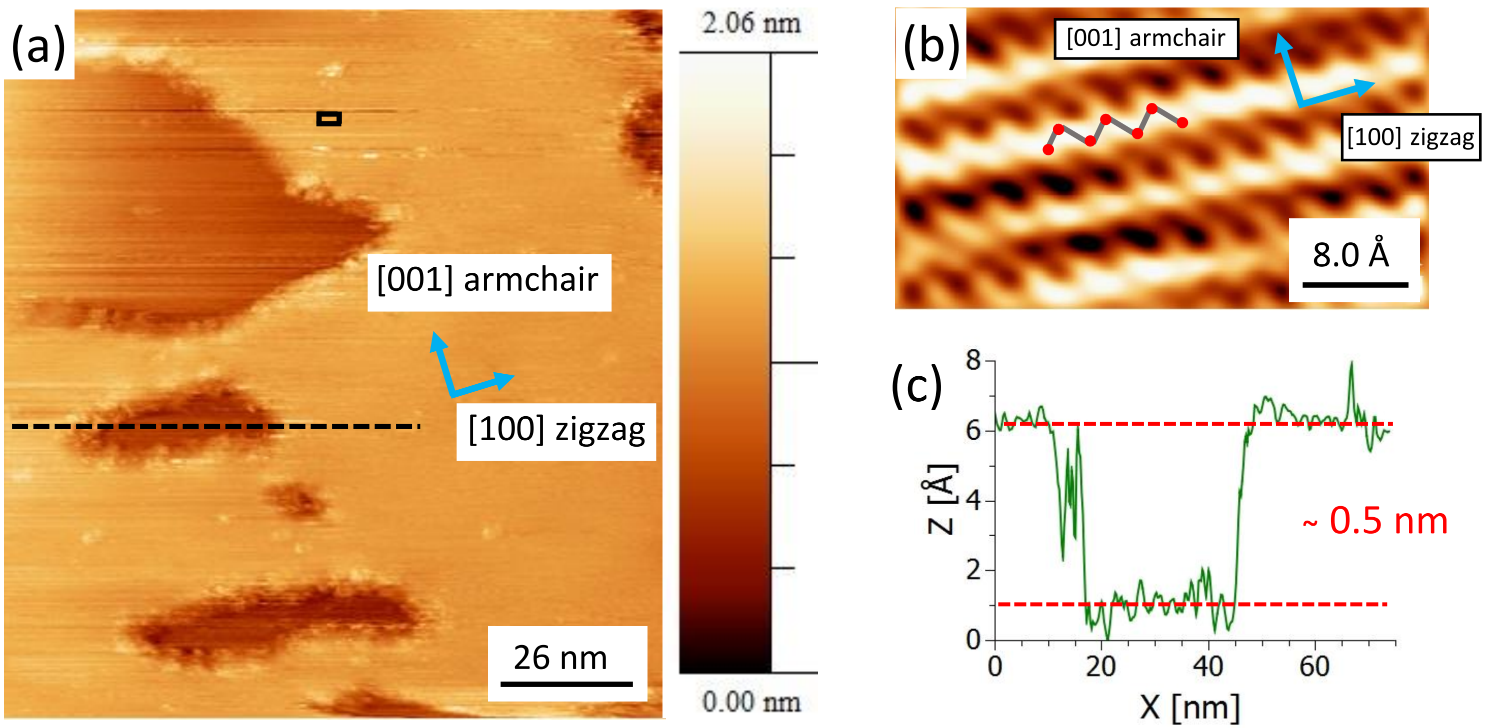
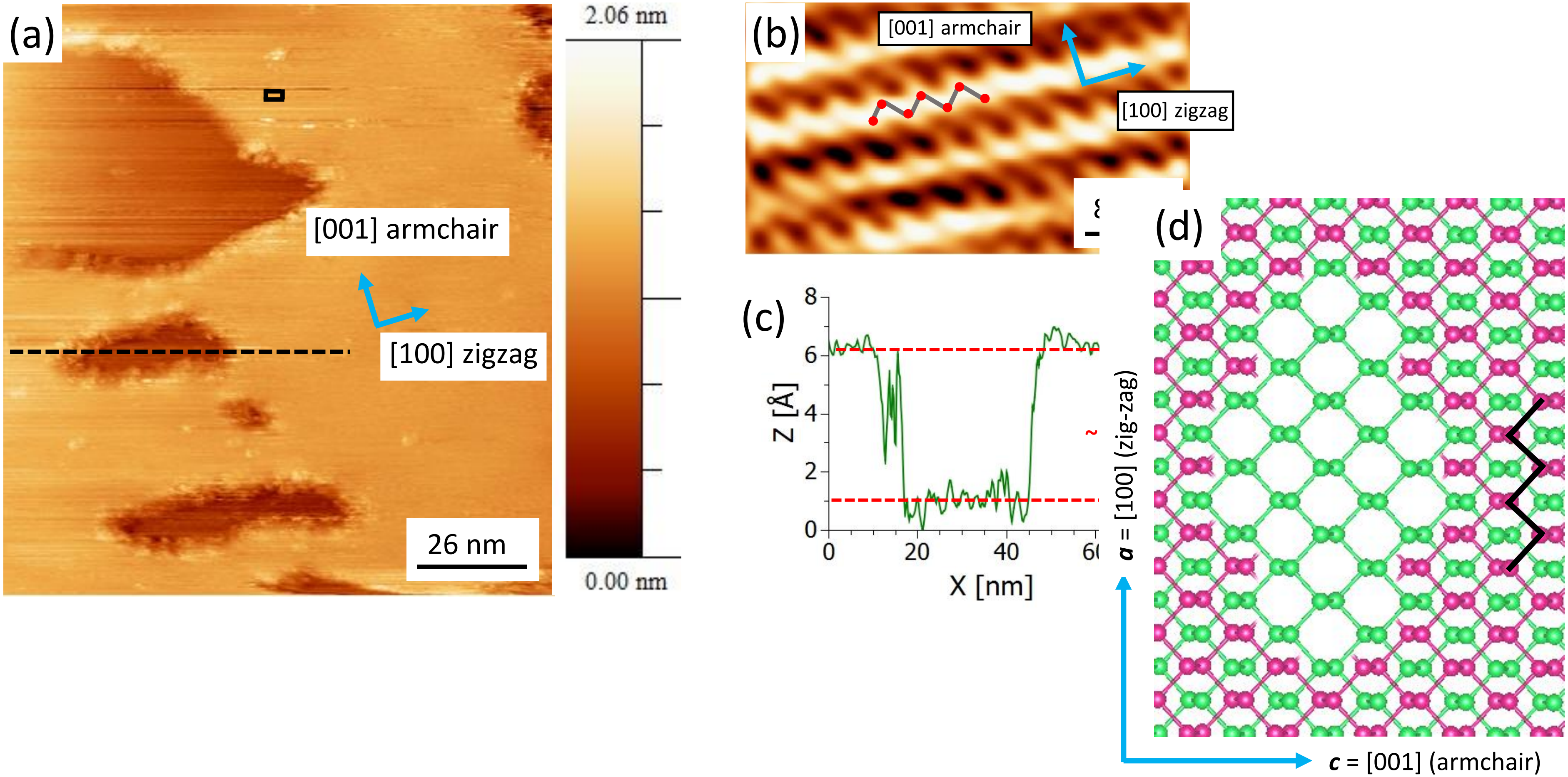
Crater alignment



Abhishek Kumar et al., J. Phys. Chem. C, submitted.

Crater alignment



Abhishek Kumar et al., J. Phys. Chem. C, submitted.

bP devices

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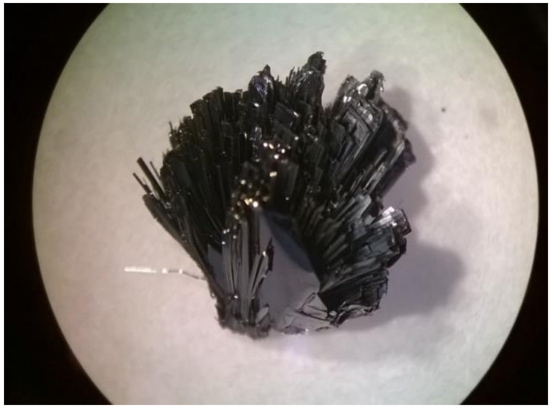
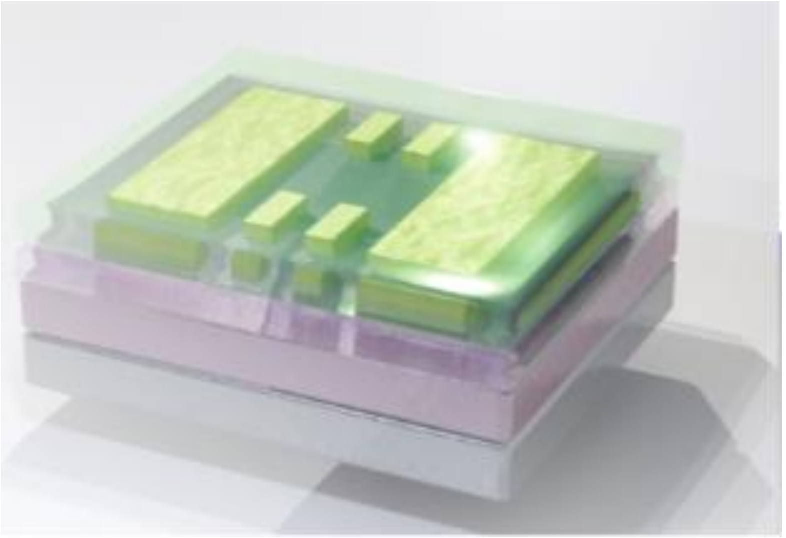
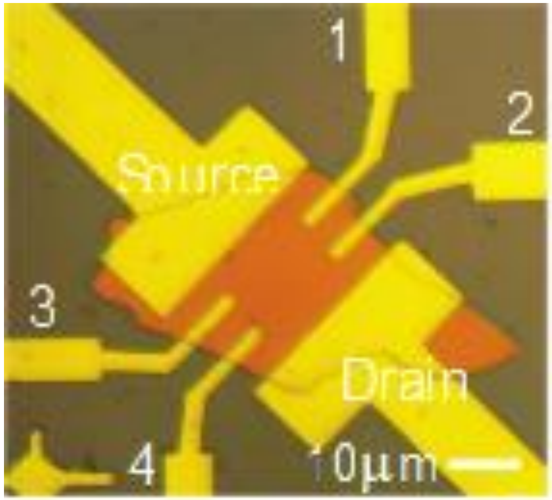
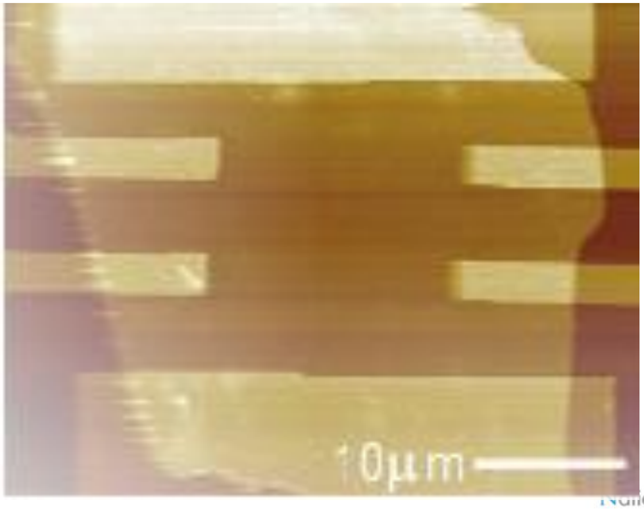
bP Field Effect Transistor





PMMA
MMA
Ti/Au contacts
bP flake
HMDS
SiO_2 thermal oxide
Si



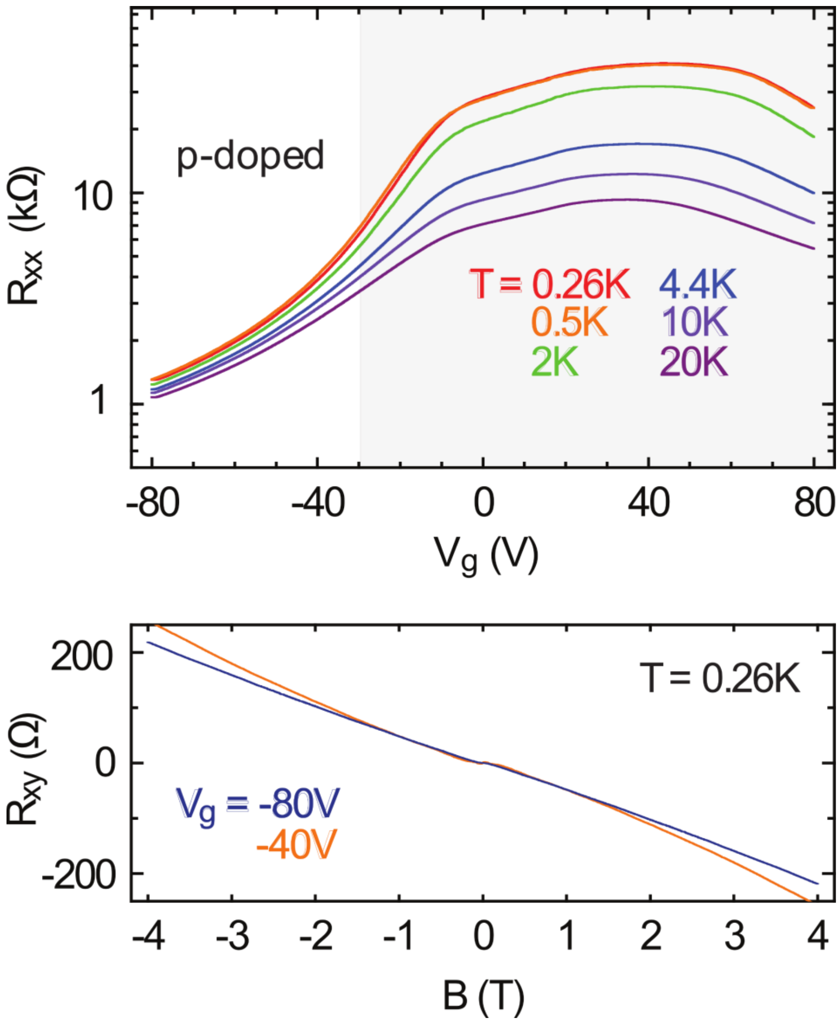


R_{xx}: 1-2
R_{xy}: 1-3

Flake thickness:
65 ± 2 nm

N. Hemsworth *et al.*, Phys. Rev. B **94**, 245404 (2016).

Transport Characterization

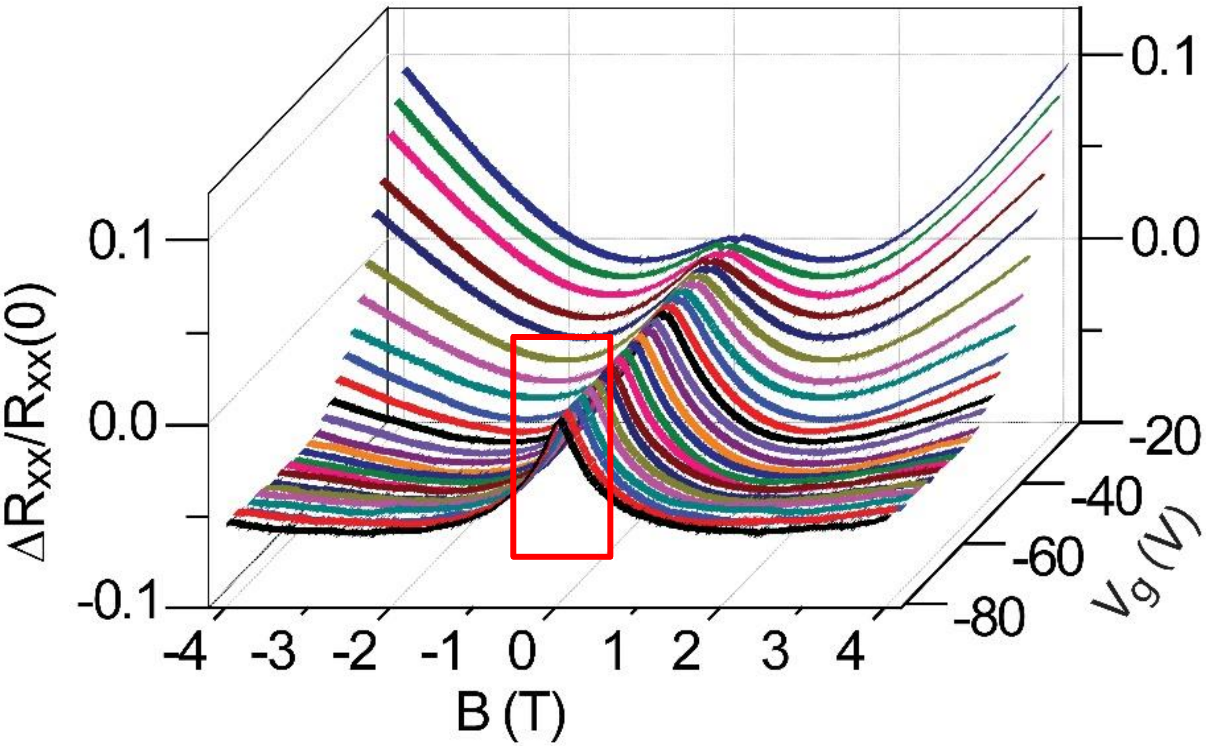


- p ~ V_g for V_g < -30 V
- p = 10^{13} cm^{-2} for V_g = -30 V
- Field-effect mobility μ: 300 cm^2/Vs at V_g = -70 V
- Negligible T-dependence in μ for 0.26 K < T < 20 K

N. Hemsworth *et al.*, Phys. Rev. B **94**, 245404 (2016).

Longitudinal magnetotransport measurements

T = 300 mK



N. Hemsworth *et al.*, Phys. Rev. B **94**, 245404 (2016).

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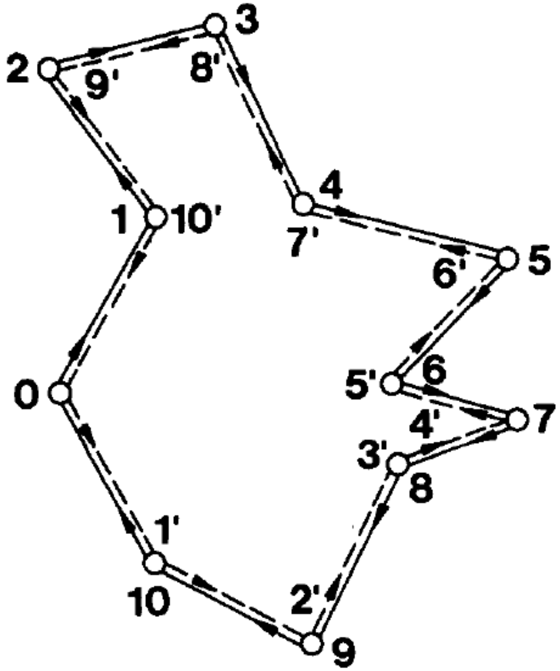
Weak Localization

Weak localization is a quantum effect related to coherent scattering at low temperatures.



Picture from Bergmann, Weak localization in thin films, Physics Reports 107, 1984

Amplitude A_1 Amplitude A_2

Normal Diffusion Model:

$$P = |A_1|^2 + |A_2|^2 = 2\ |A|^2$$

Coherent Addition:

$$P = |A_1 + A_2|^2 = |2\ A|^2 = 4\ |A|^2$$

Since weak localization is a coherent scattering effect:

- It's suppressed by magnetic field
- It's smeared by temperature

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Weak Localization

$$\Delta\sigma = -\frac{e^2}{2\pi^2\hbar}\left(\Psi\left(\frac{1}{2}+\frac{B_1}{B}\right)-\Psi\left(\frac{1}{2}+\frac{B_2}{B}\right)+\frac{1}{2}\Psi\left(\frac{1}{2}+\frac{B_3}{B}\right)-\frac{1}{2}\Psi\left(\frac{1}{2}+\frac{B_2}{B}\right)\right), \quad (1)$$

where Ψ is the digamma function. The field parameters in the above expression are given by:

$$B_1 = B_0 + B_{so} + B_s \quad (2)$$

$$B_2 = \frac{4}{3}B_{so} + \frac{2}{3}B_s + B_\phi \quad (3)$$

$$B_3 = 2B_s + B_\phi \quad (4)$$

S. Hikami, A. I. Larkin, and Y. Nagaoka,
Prog. Of Theor. Phys. 63 (1980) 707.

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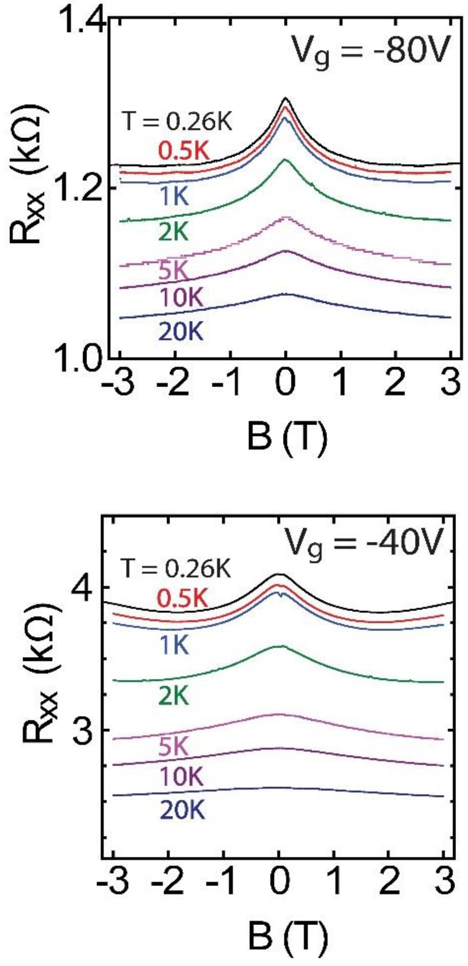
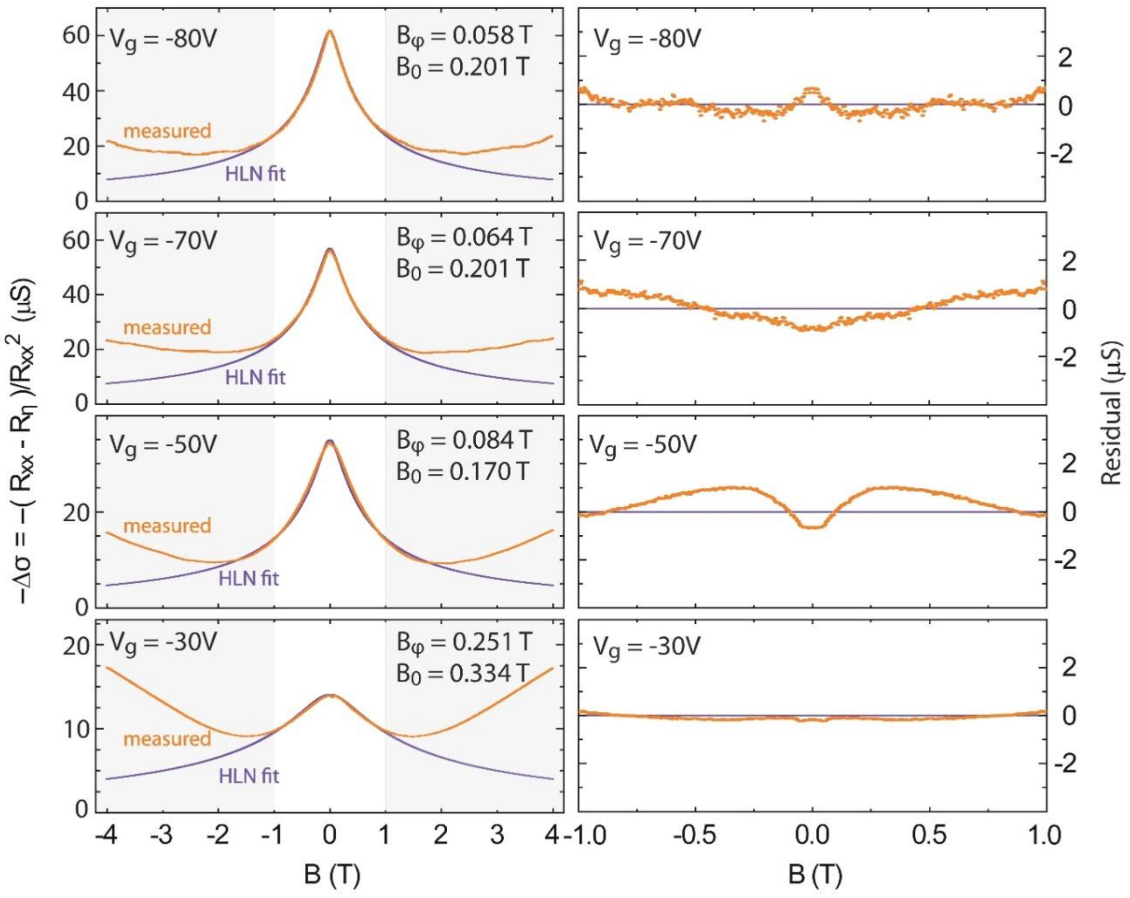
Weak Localization



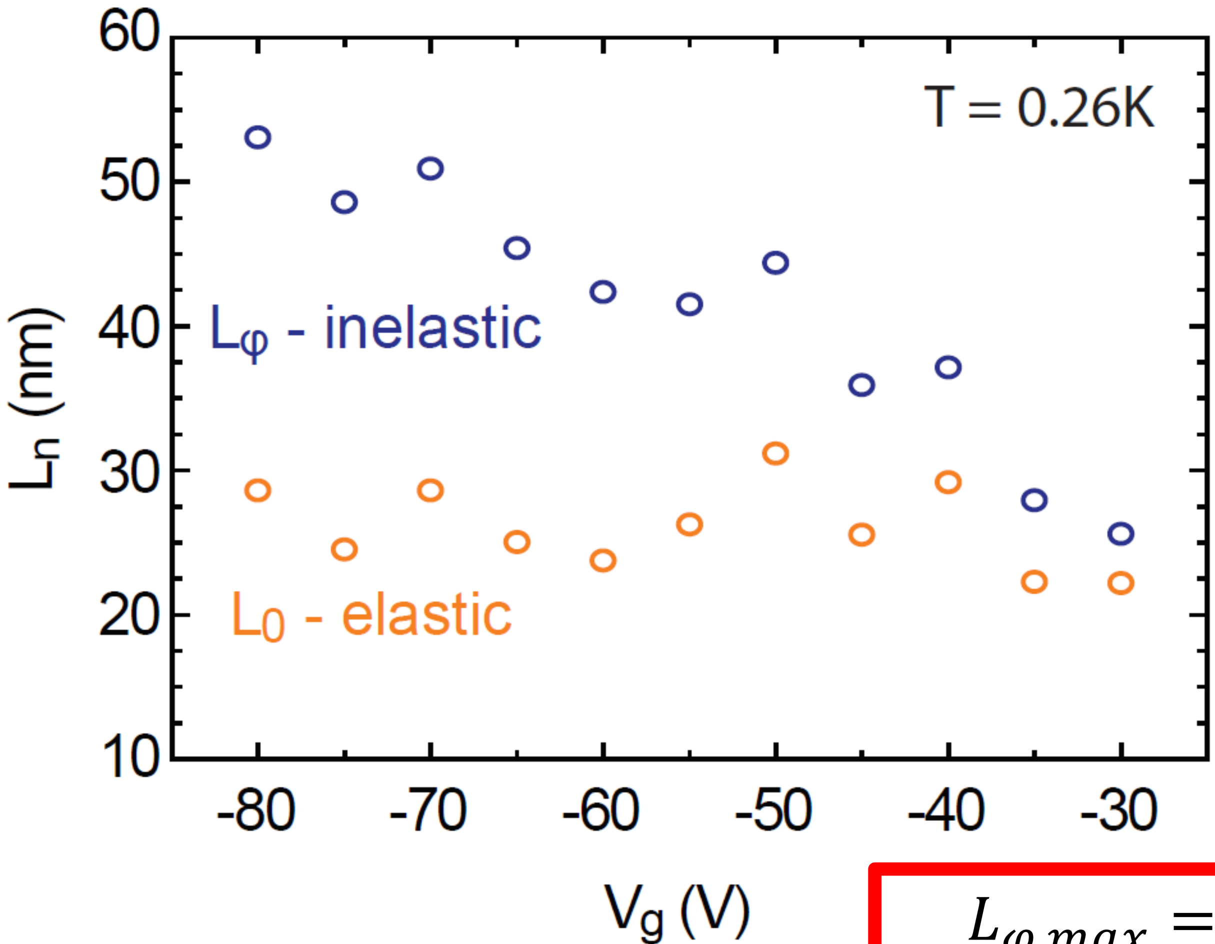
T = 0.26 K



N. Hemsworth *et al.*, Phys. Rev. B **94**, 245404 (2016).

Scattering Lengths

$BL^2 = h/4e$



$$L_{\varphi,max} = 55\ nm$$

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N. Hemsworth *et al.*, Phys. Rev. B **94**, 245404 (2016).

Scattering Lengths

- Ballistic transport: $\tau_\varphi \propto T^{-2}$
- Diffusive transport ($\tau_0 < \tau_\varphi$):

Dephasing length vs. inelastic scattering time:

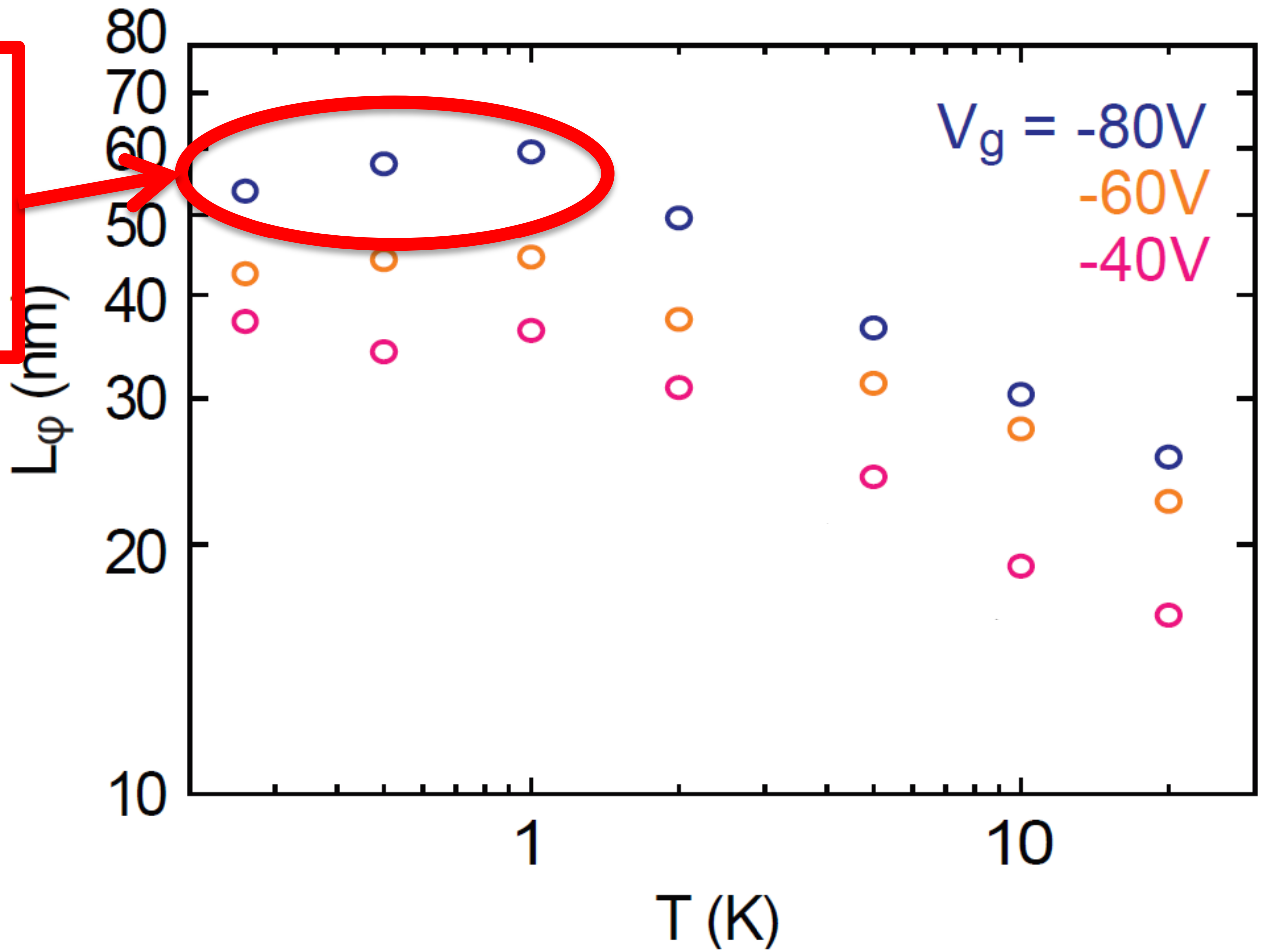
$L_\varphi = \sqrt{D\tau_\varphi}$ with *D* diffusion coefficient

$\tau_\varphi \propto T^{-1}$ or $L_\varphi \propto T^{-1/2}$

Lin and Bird, Jour. Phys. Cond. Mat. 14, R501, (2002)

Scattering Lengths

Saturation most likely due to dynamical impurities.



N. Hemsworth *et al.*, Phys. Rev. B **94**, 245404 (2016).

Scattering Lengths

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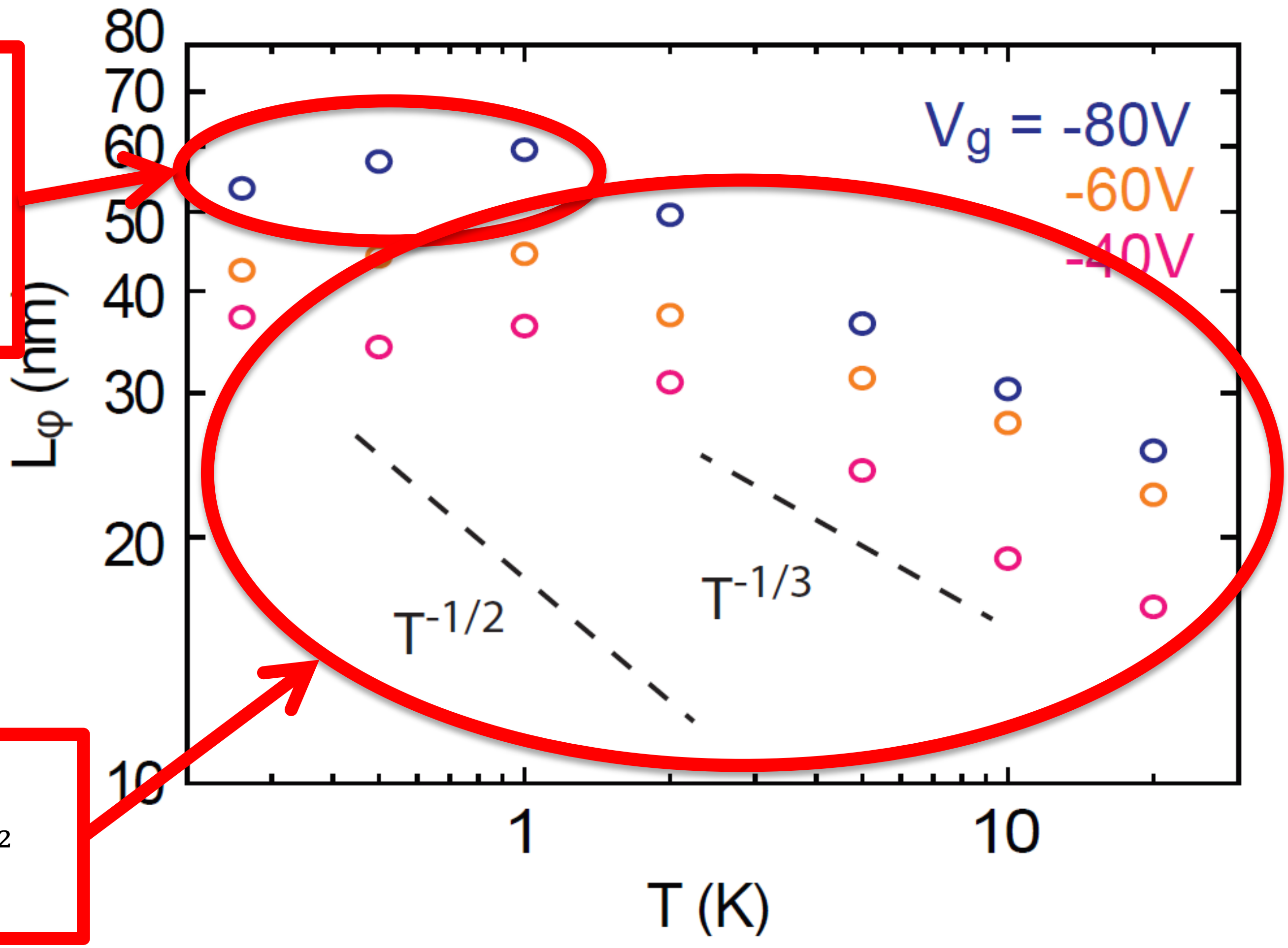

L_φ does not follow a $T^{-1/2}$ behaviour.

N. Hemsworth *et al.*, Phys. Rev. B **94**, 245404 (2016).

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Quasi-1D systems

VOLUME 86, NUMBER 9 PHYSICAL REVIEW LETTERS 26 FEBRUARY 2001

Geometry-Dependent Dephasing in Small Metallic Wires

D. Natelson, R. L. Willett, K. W. West, and L. N. Pfeiffer
Bell Laboratories, Lucent Technologies, Murray Hill, New Jersey 07974
(Received 19 June 2000)

Temperature dependent weak localization is measured in metallic nanowires in a previously unexplored size regime down to width $w = 5$ nm. The dephasing time, τ_ϕ, shows a low temperature T dependence close to quasi-1D theoretical expectations ($\tau_\phi \sim T^{-2/3}$) in the narrowest wires, but exhibits a relative saturation as $T \to 0$ for wide samples of the same material, as observed previously. As only sample geometry is varied to exhib
constraint on models of dephasing

PHYSICAL REVIEW B, VOLUME 64, 121404(R)

Phase-coherent transport in ropes of single-wall carbon nanotubes

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IBM T. J. Watson Research Center, Yorktown Heights, New York 10598

H. Stahl, U. Th. Hunger, and B. Lengeler
II. Physikalisches Institut, RWTH Aachen, Templergraben 55, 52056 Aachen, Germany
(Received 21 May 2001; revised manuscript received 23 July 2001; published 6 September 2001)

To study the phase breaking scattering events in single-wall carbon nanotubes (SWNTs), ropes of SWNTs are intentionally damaged by Ar^+ ion milling. Due to this treatment, the average distance an electron can travel before being elastically scattered is reduced to about 10 nm. This significantly increases the probability of one-dimensional localization and allows us to obtain the phase coherence length (L_Φ) in ropes of SWNTs as a function of temperature. We find that Nyquist scattering ($\tau_\Phi \sim T^{-2/3}$) as well as another dephasing mechanism with a $\tau_\Phi \sim T^{-1}$ dependence are involved in limiting the phase-coherent transport. We also investigate the scattering of hot electrons in the system. The results support the statement that two different scattering mechanisms dominate the phase coherence length for different rope samples.

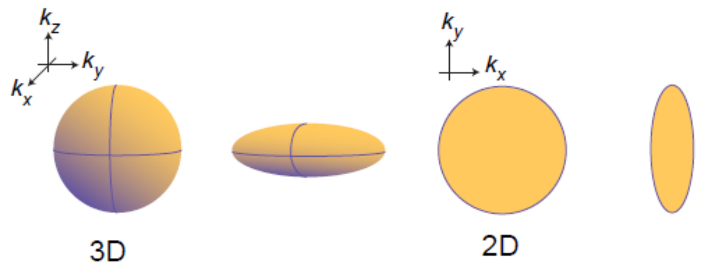
Comparison with quasi-1D wires

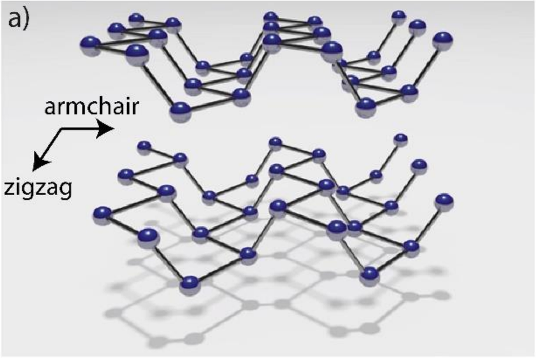
D. Natelson et al.
PRL 86 (2009):

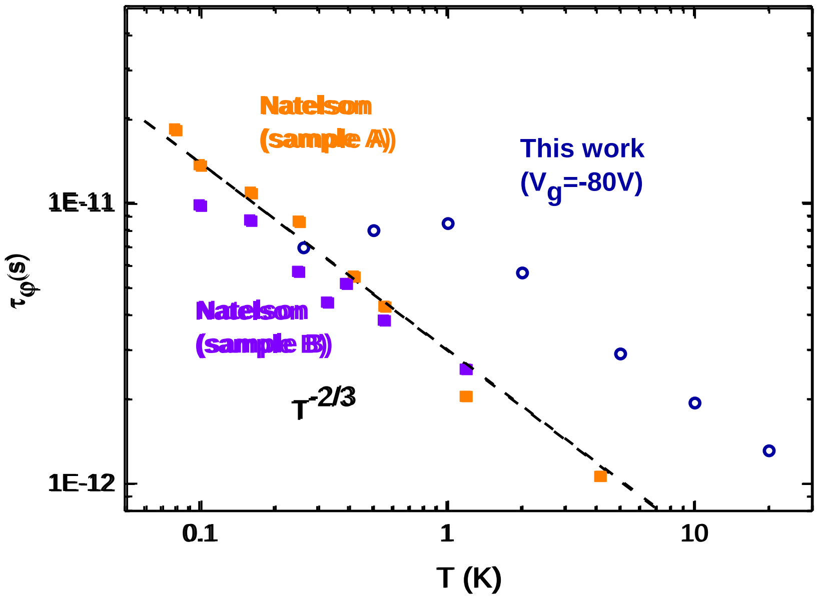
quasi-1D:
$$L_\varphi, L_T > w, t$$

width w
thickness t

$$\tau_\varphi \propto T^{-2/3}$$
$$L_\varphi \propto T^{-1/3}$$





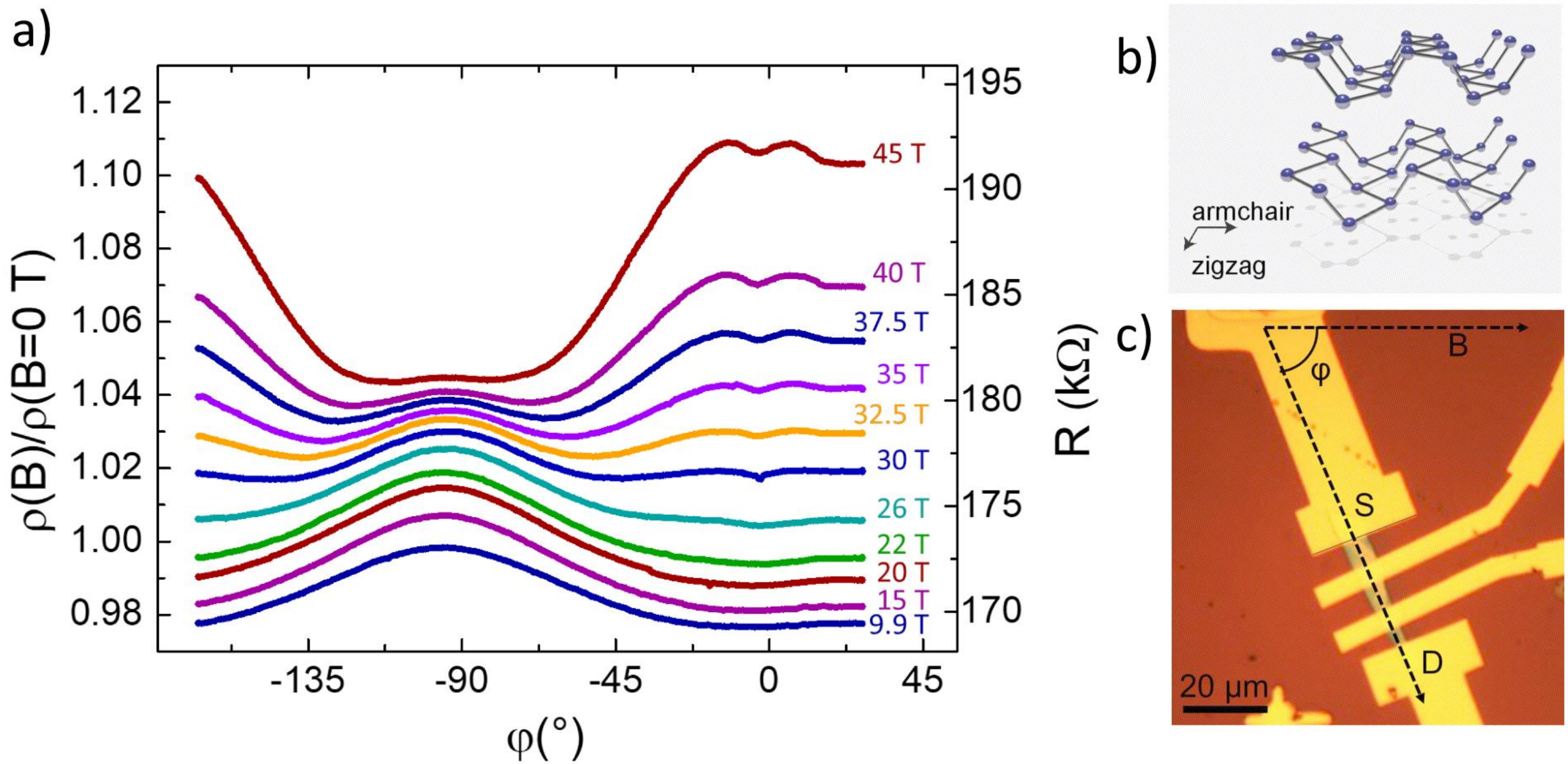


$$L_\varphi = 55\ nm$$

thermal length:
$$L_T = \sqrt{\hbar D / k_B T}$$
= 10 – 60 nm

N. Hemsworth *et al.*, Phys. Rev. B **94**, 245404 (2016).

Strong anisotropic in-plane magneto-transport in a few-layer bP FET

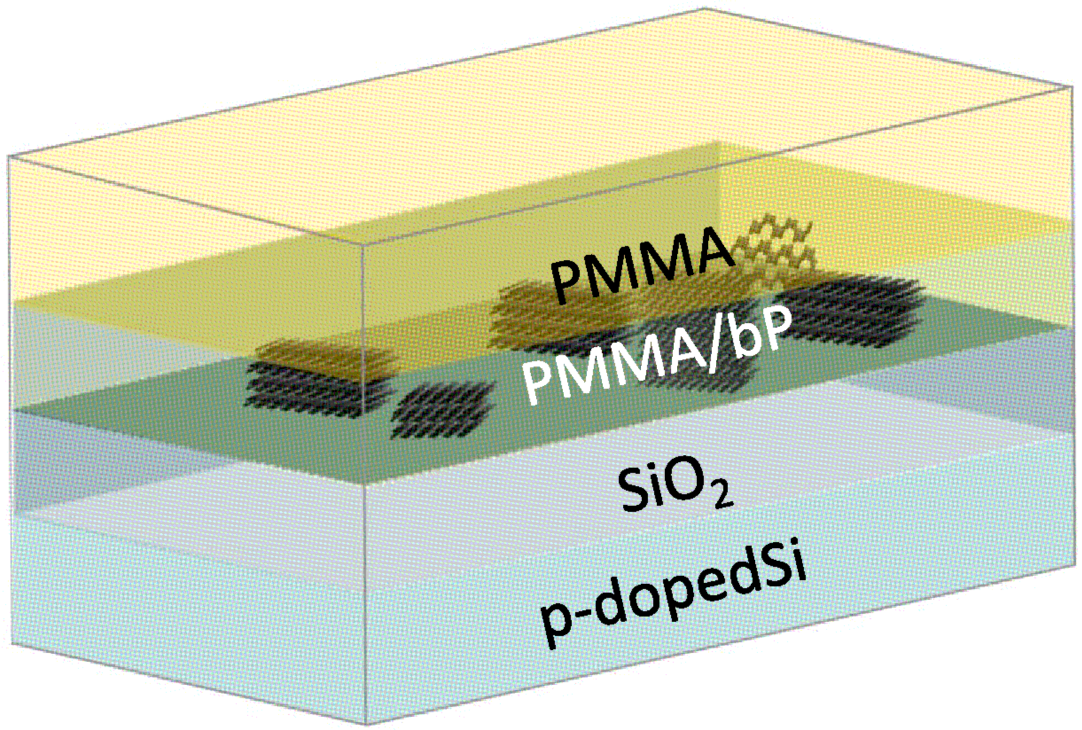


F. Telesio et al., unpublished.

bP / PMMA hybrid material

bP embedded in PMMA

prepared by in situ polymerization



F. Telesio et al., Nanotechnology, submitted.

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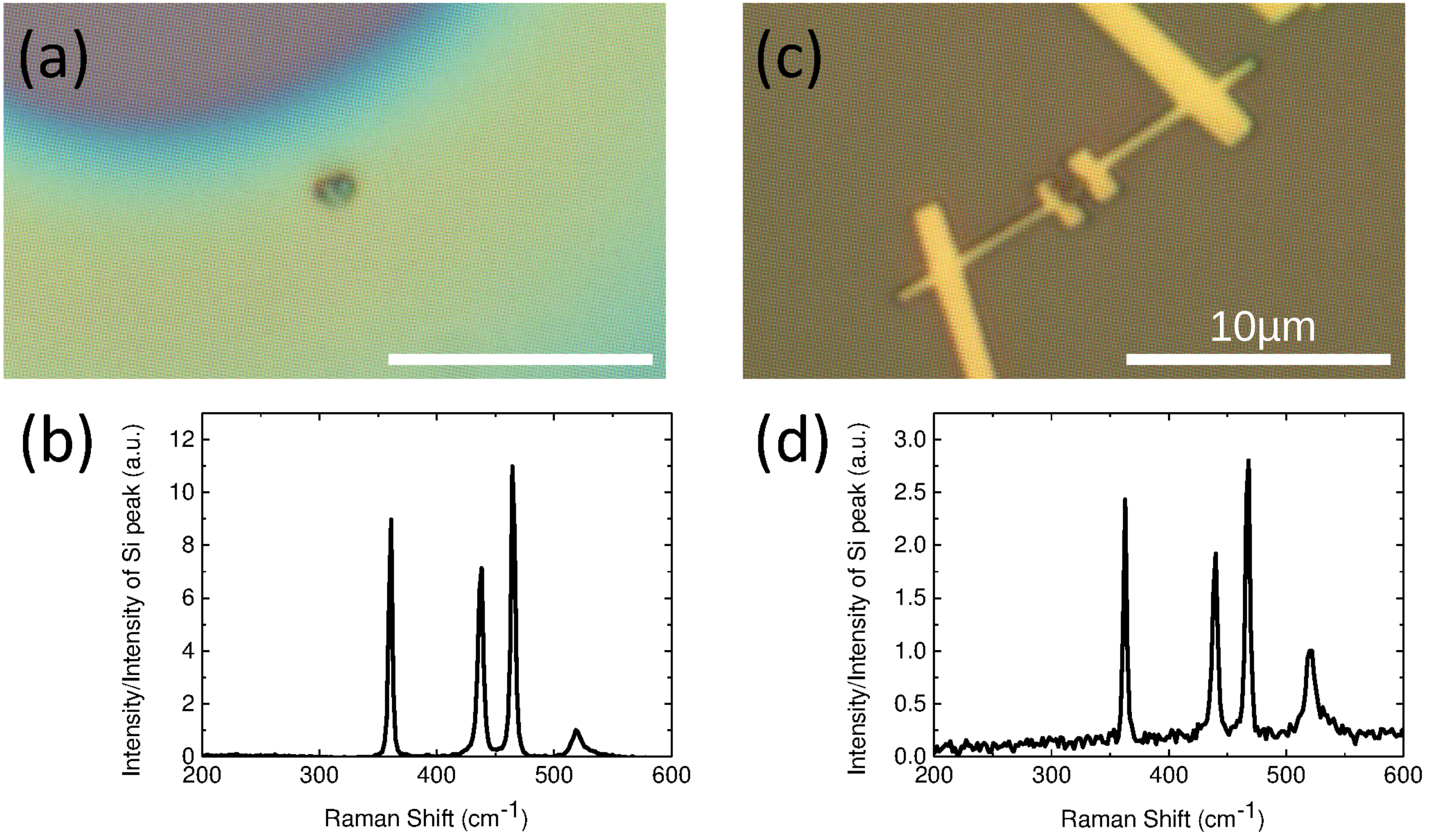
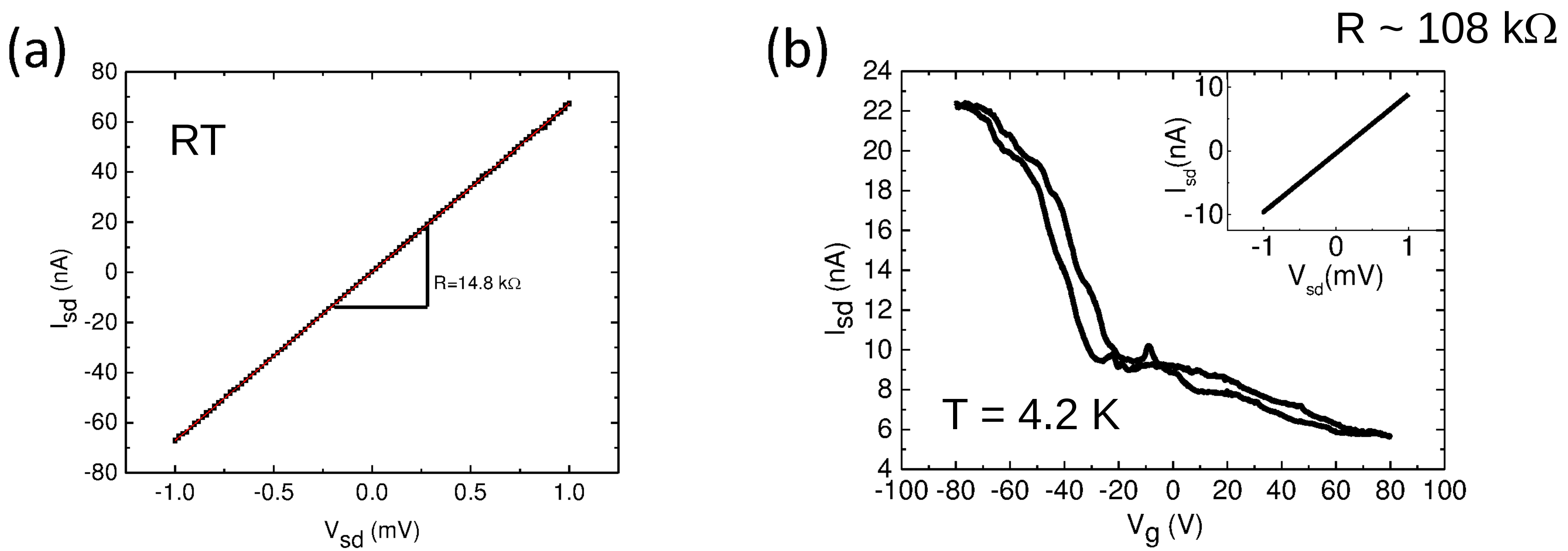
Optical microscopy and Raman spectroscopy



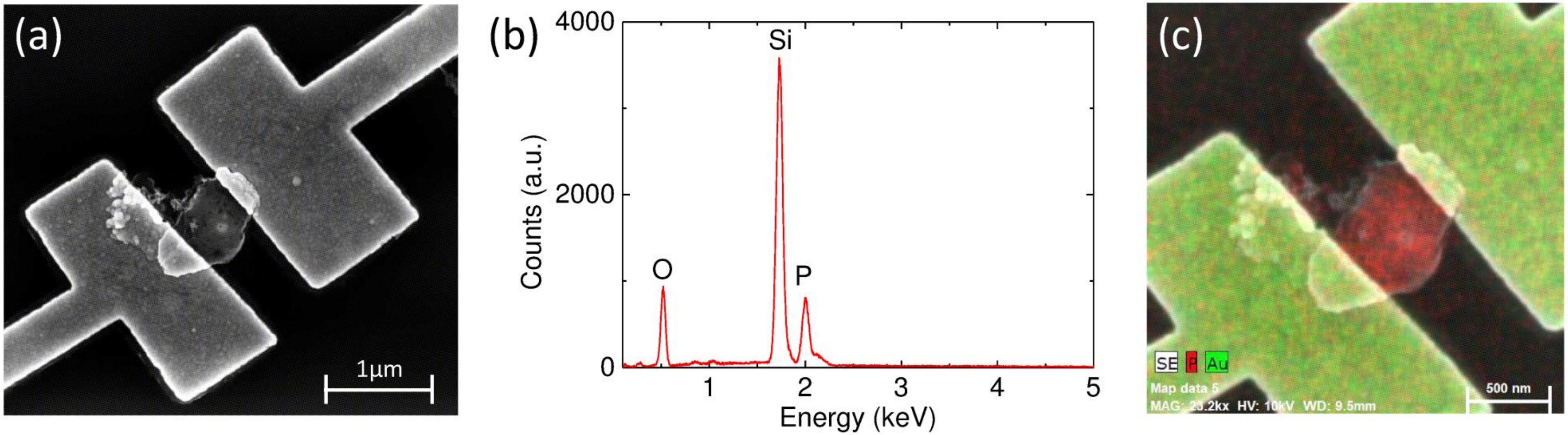
F. Telesio et al., Nanotechnology, submitted.

Transport properties



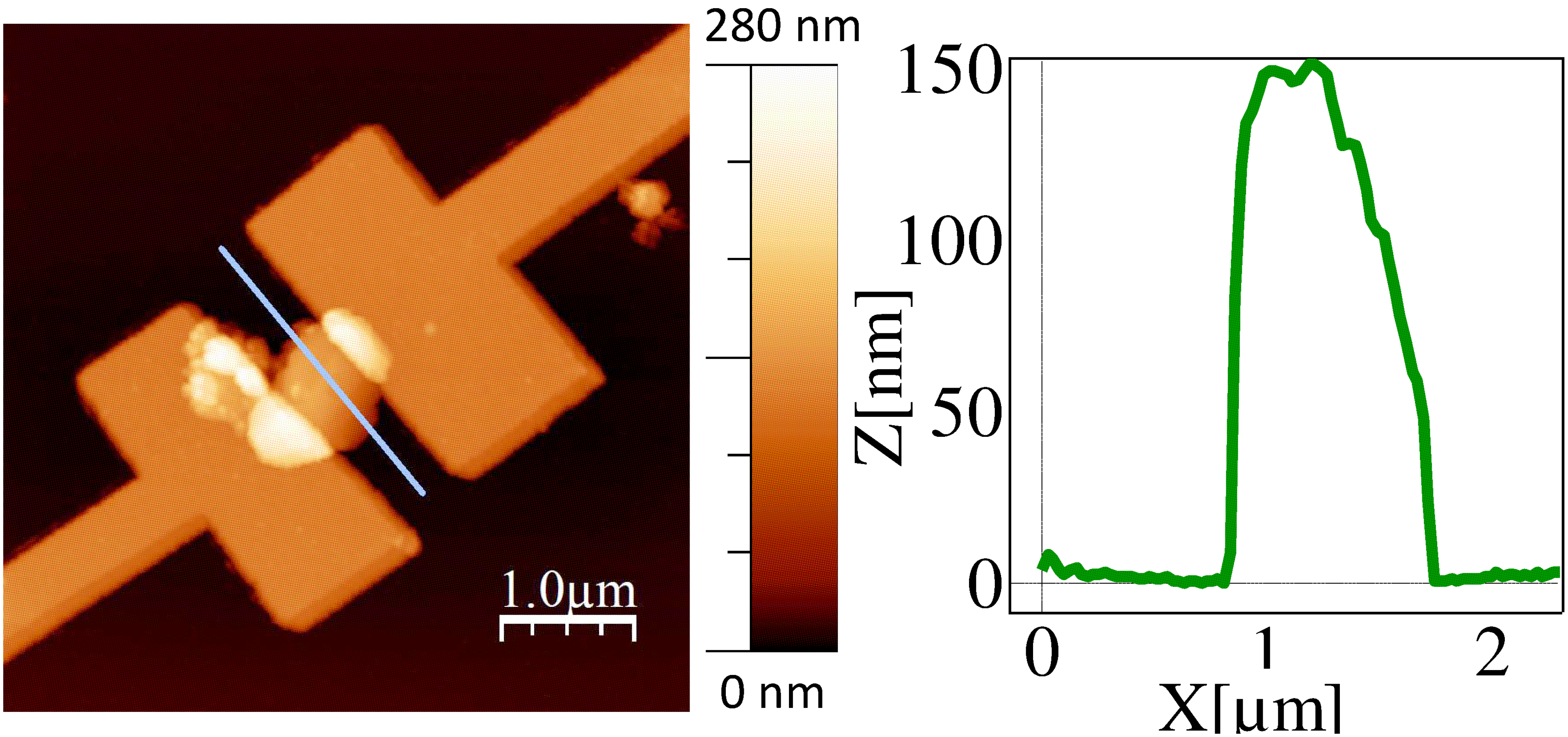
F. Telesio et al., Nanotechnology, submitted.

SEM + EDX



F. Telesio et al., Nanotechnology, submitted.

AFM



F. Telesio et al., Nanotechnology, submitted.

Coworkers

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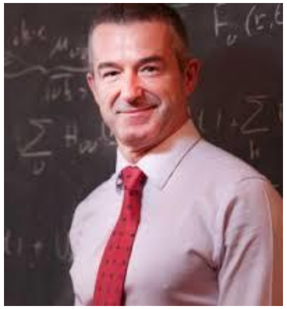

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SEED project

Thank you for your attention!

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