Dephasing in Strongly Anisotropic Black Phosphorus

Francesca Telesio

Modena, 20/03/2017

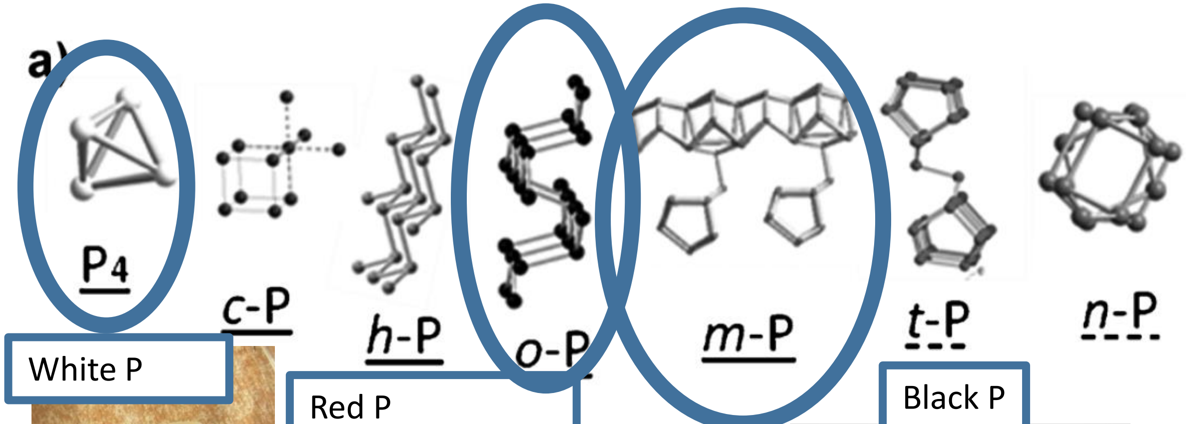
National Enterprise for nanoScience and nanoTechnology

NEST

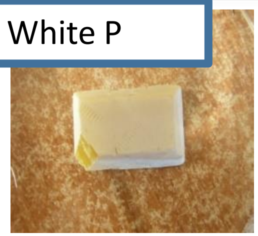
Summary

- Introduction: black Phosphorus
- Dephasing in black Phosphorus
  - Weak localization measurements
  - Data analysis and interpretation
  - Conclusions
- Outlooks: SEED project – STM on few-layer black Phosphorus

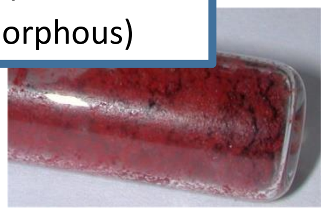
The family of phosphorus alloys



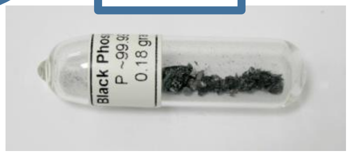
White P



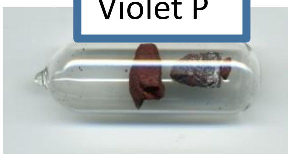
Red P (amorphous)

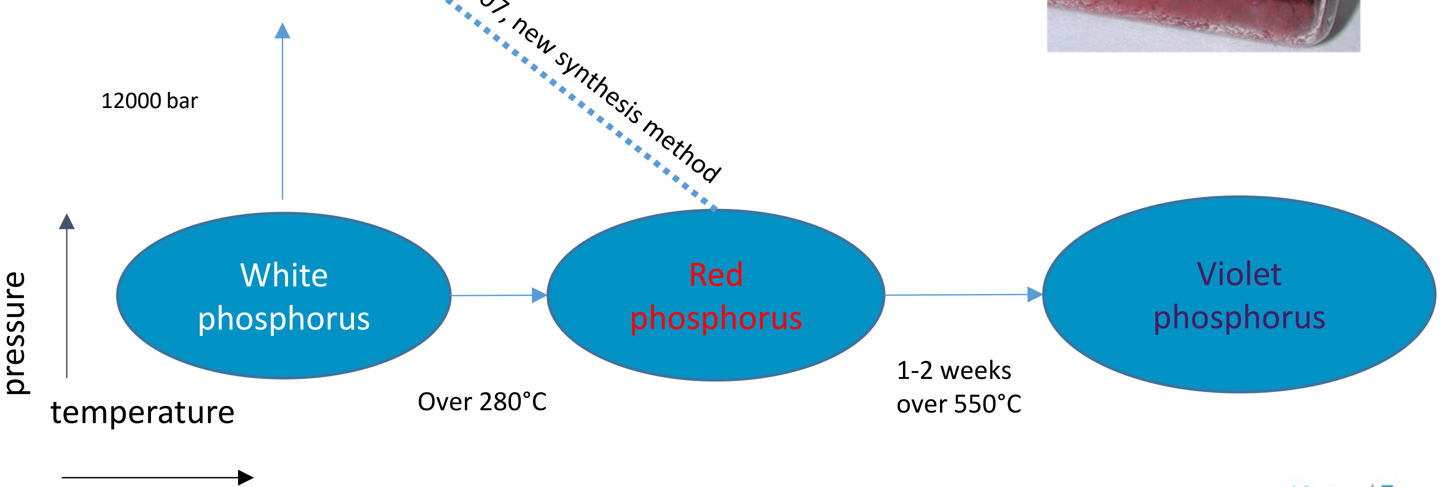


Black P



Violet P





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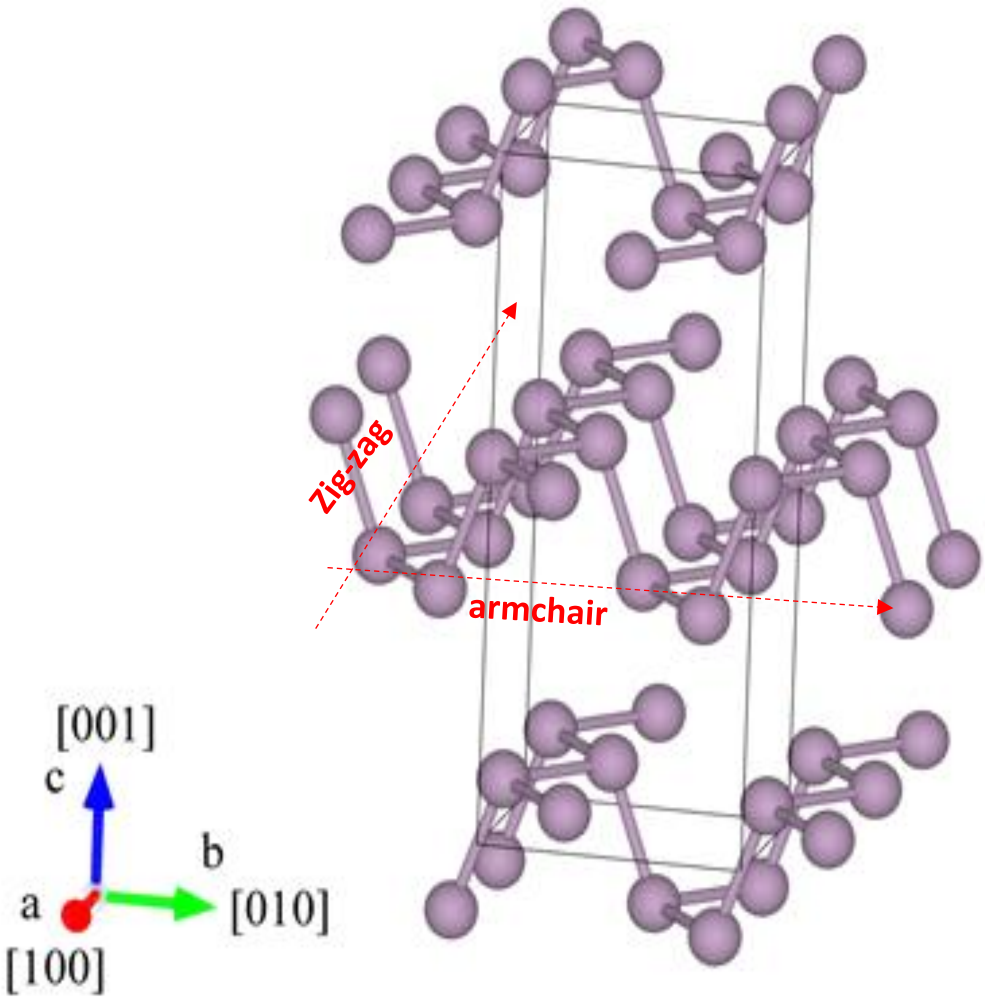
F. Bachhuber et al., Angew. Chem. Int. Ed. 53 (2014) 11629

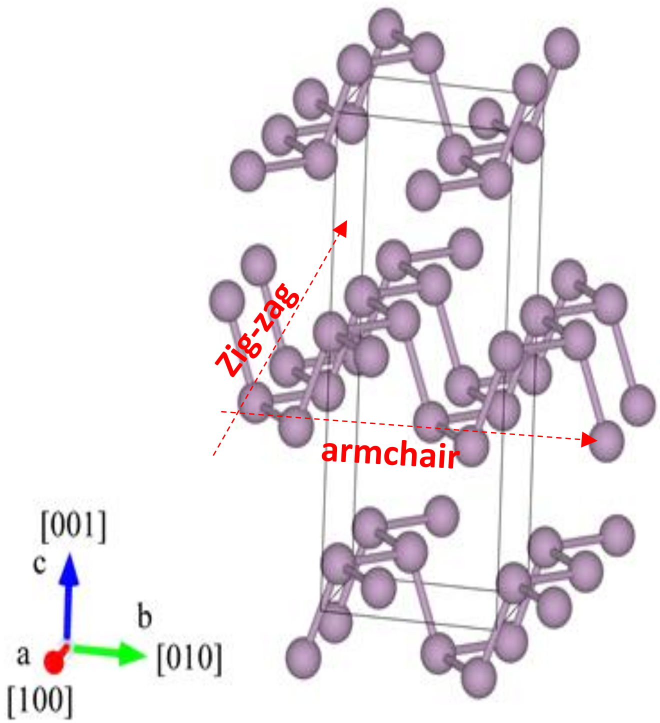
Black phosphorus



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

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

Black phosphorus

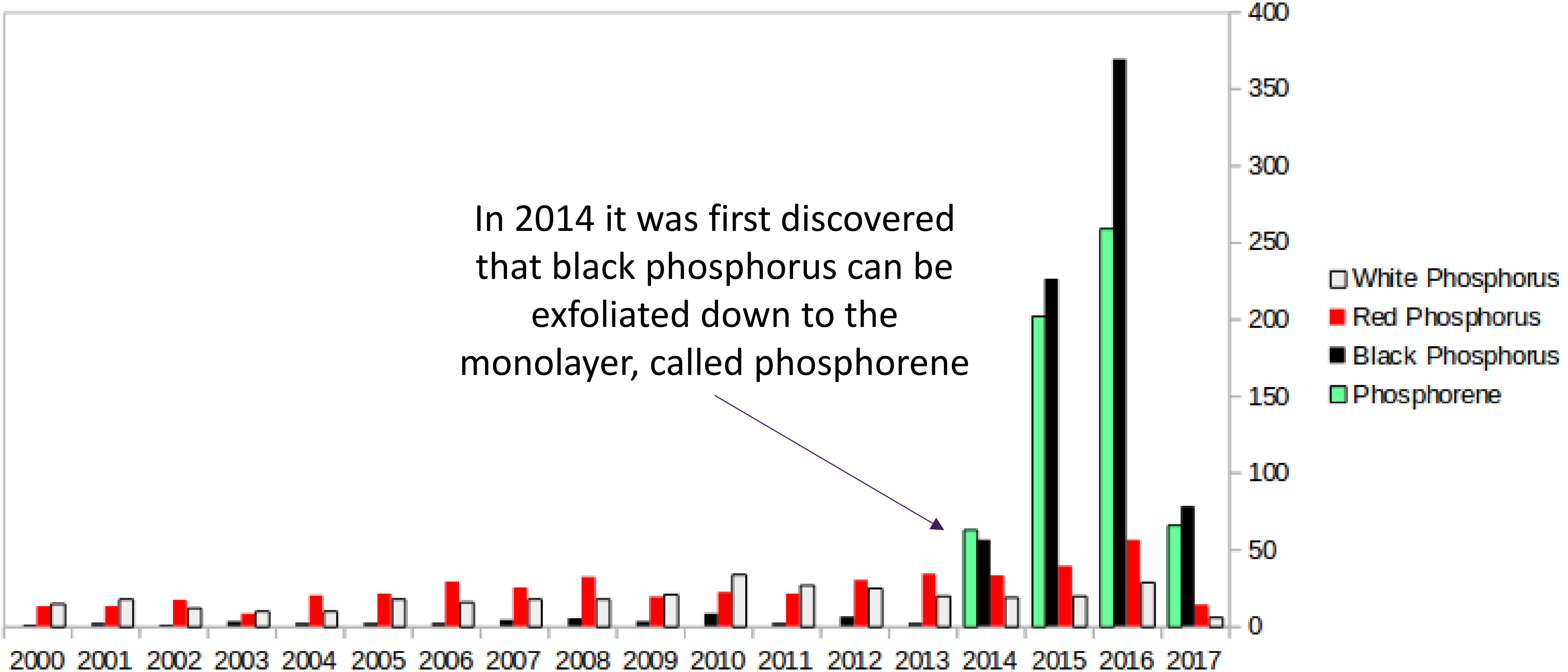


Cell parameters
a=3.13Å
b=10.47Å
c=4.37Å

- ✓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 cm^2/Vs @ 20 K)
- ✓1983 (Narita): n-type doping by Te

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

The Renaissance of Black Phosphorus



In 2014 it was first discovered that black phosphorus can be exfoliated down to the monolayer, called phosphorene

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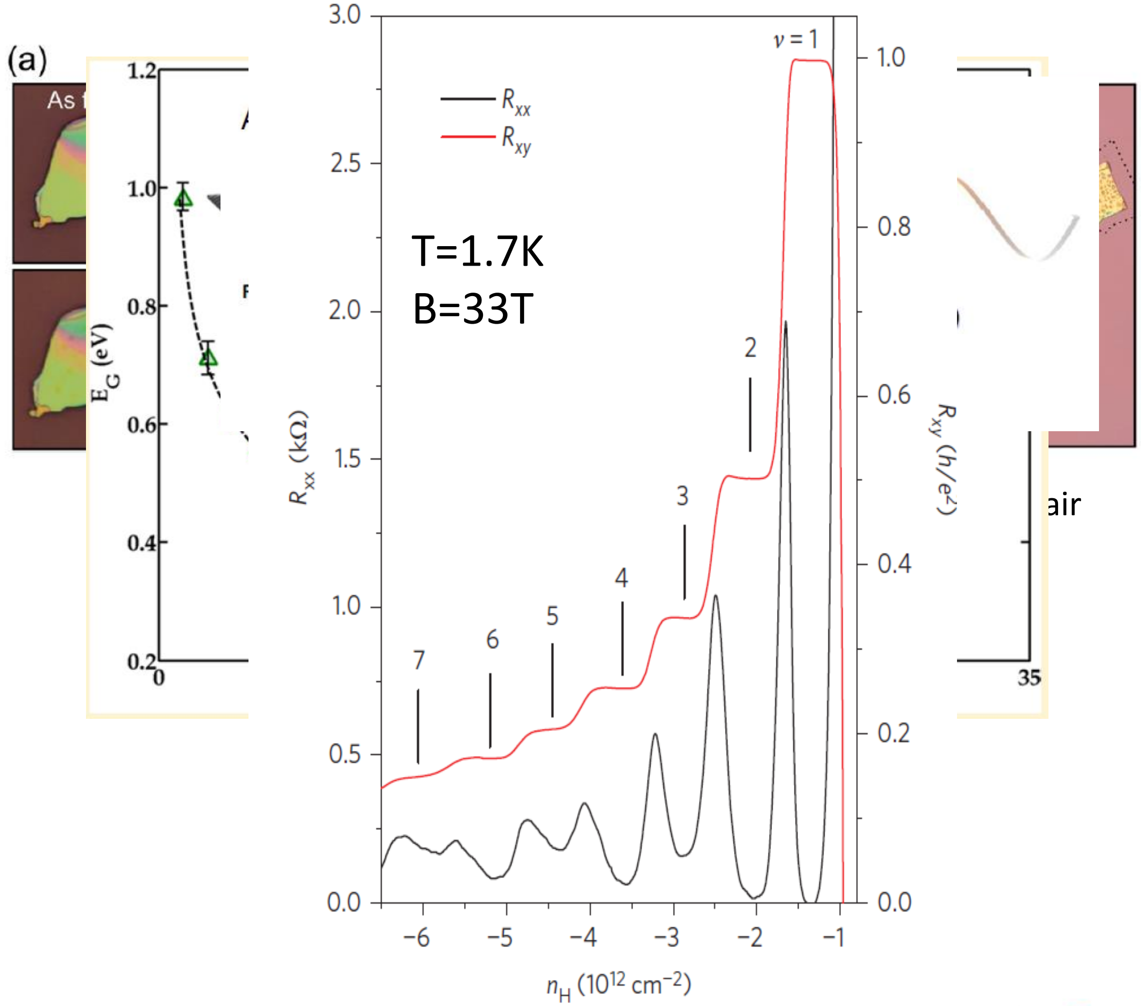
The renaissance of black phosphorus

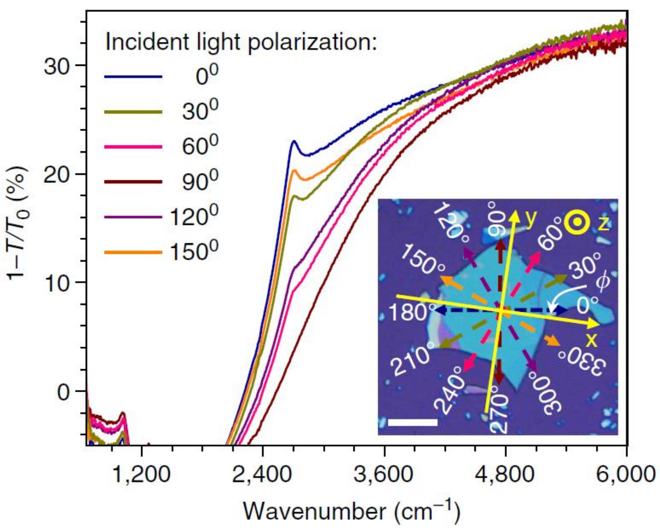
- ✓Highly reactive in air
- ✓Direct band gap
- ✓Band-gap tunable with layer number
- ✓And much more... such as some recent measurements of quantum Hall effect at high field

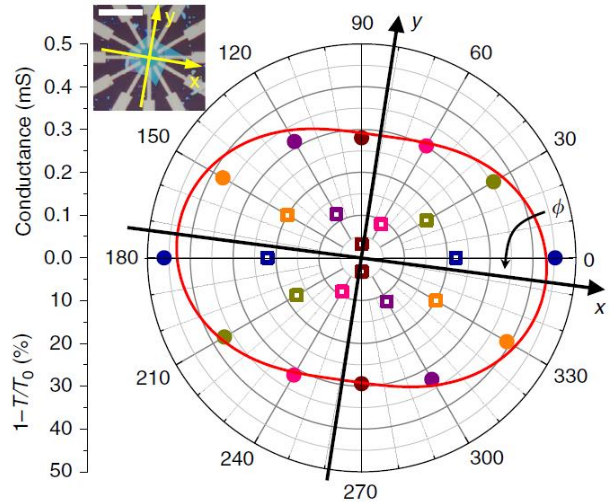


A. Castellanos-Gomez et al., 2D Mater. 1 (2014) 025001
S. Das et al., Nano Lett. 14 (2014) 5733
X. Ling et al., PNAS 112 (2015) 4523
L. Li et al., Nat. Nanotech 11 (2016), 593

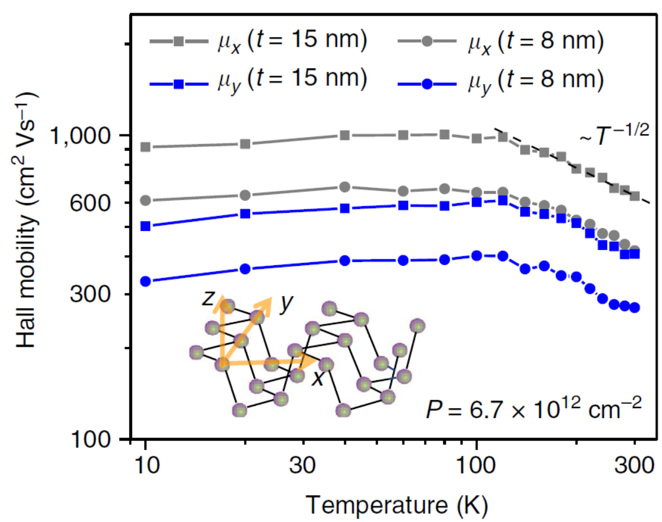
The reinassance of black phosphorus

✓ **In-plane anisotropy** of optical and transport properties





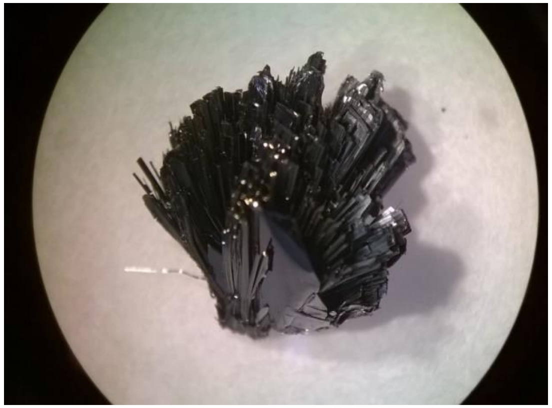
$\sigma_x/\sigma_y \approx 1.5$

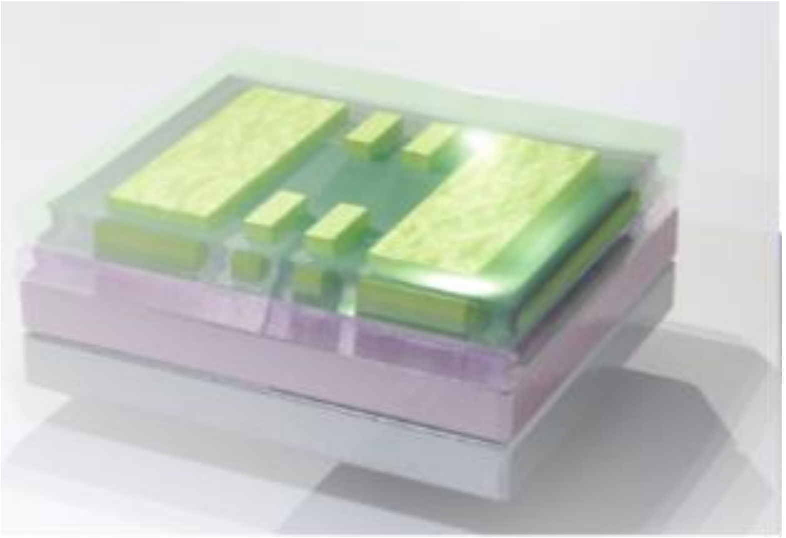


$\mu_x/\mu_y \approx 1.8$

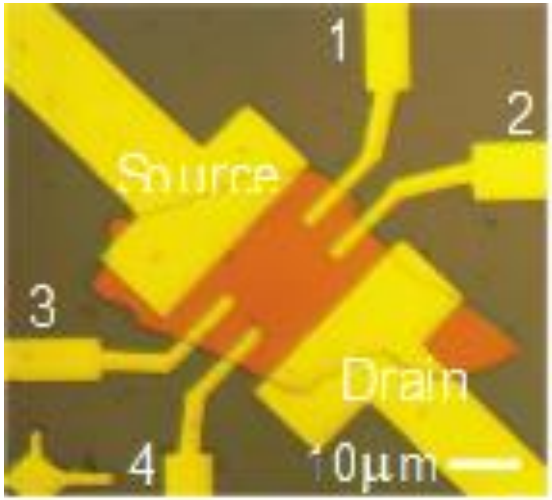
F. Xia et al., Nat. Comm. 5 (2014) 4458

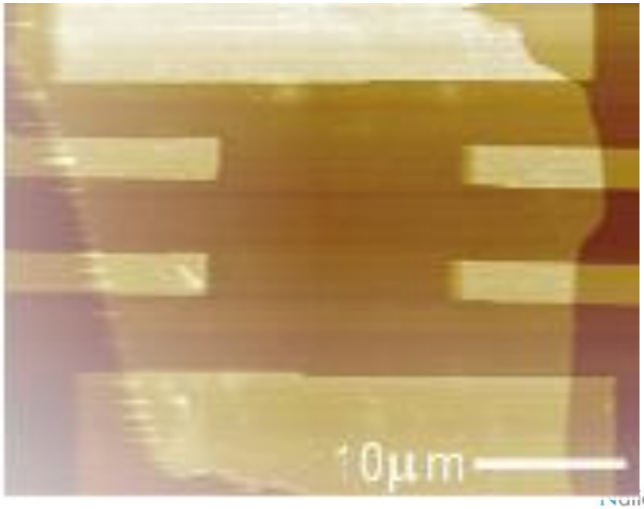
bP Field Effect Transistor





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



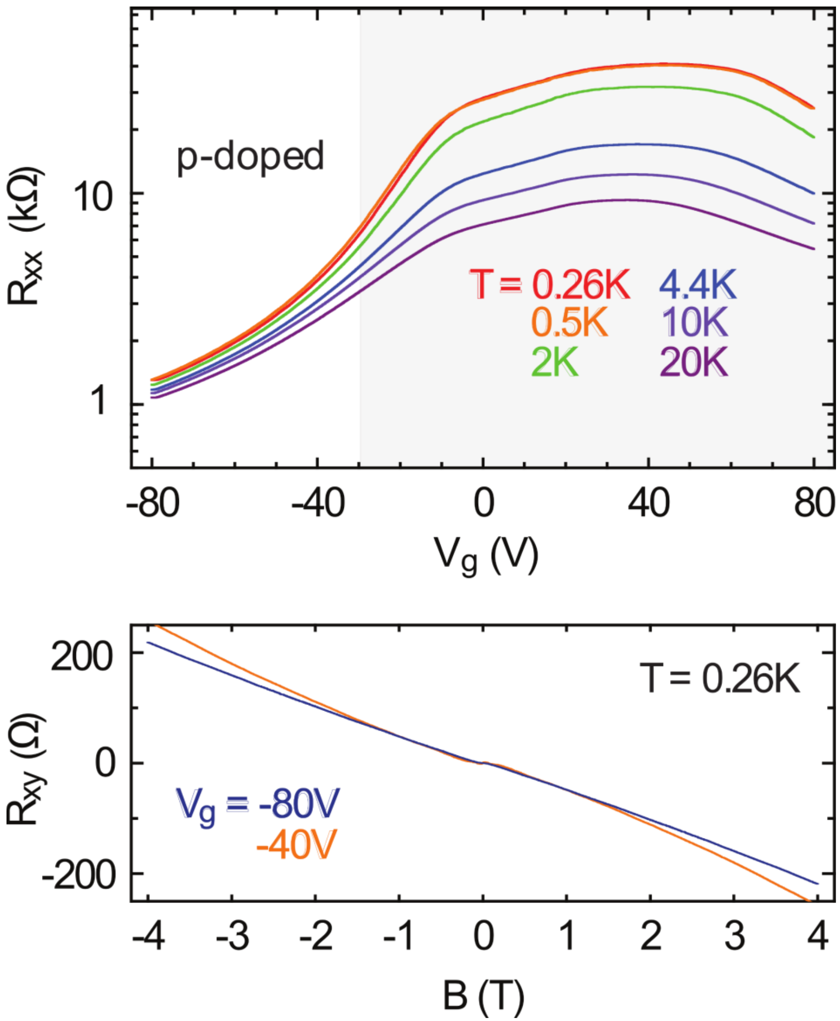


R_{xx}: 1-2
R_{xy}: 1-3

Flake thickness:
65 ± 2 nm

N.Hemsworth et al, PRB 94, 245404, (2016)

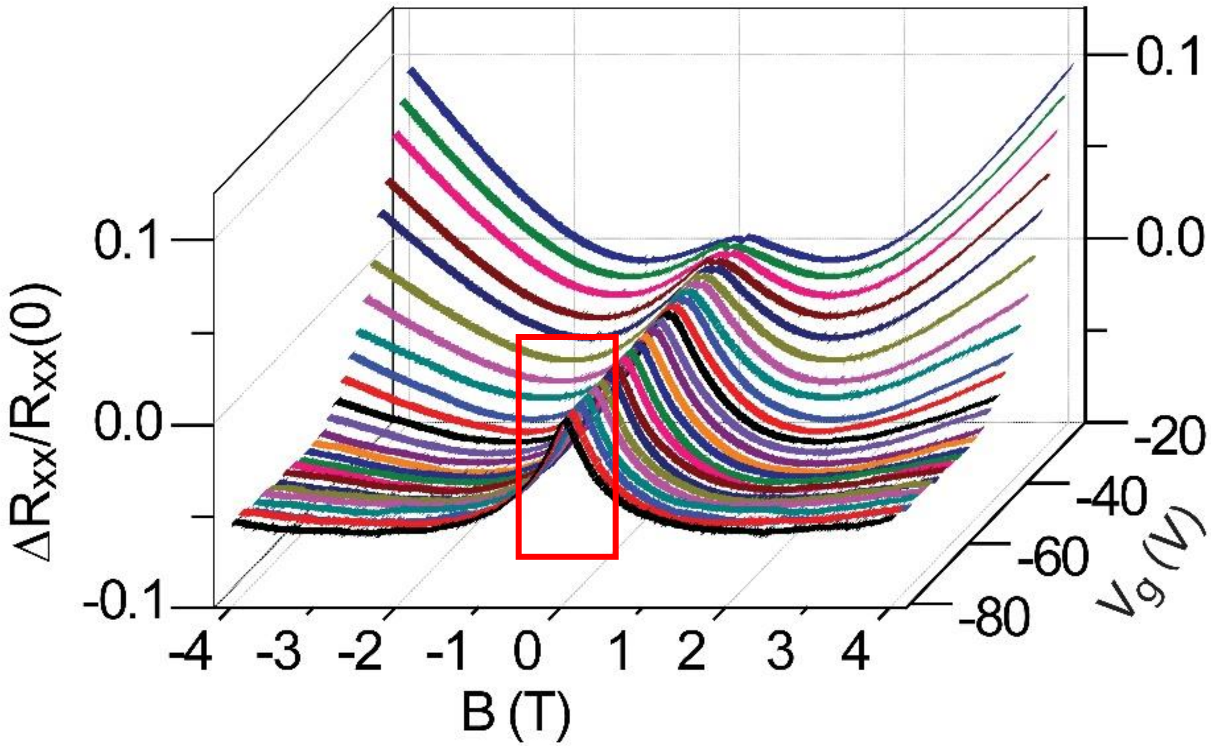
Transport Characterization



- p type 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, PRB 94, 245404, (2016)

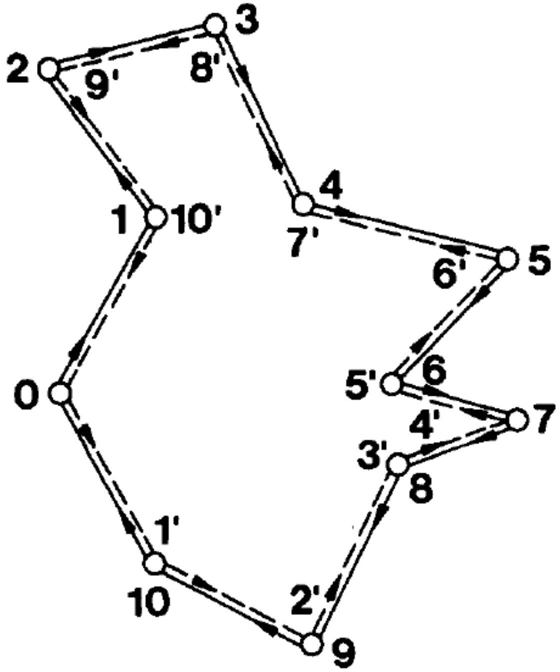
Longitudinal magnetotransport measurements



N.Hemsworth et al, PRB 94, 245404, (2016)

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 depressed by magnetic field
- It's smeared by temperature

Weak Localization: Hikami-Larkin-Nagaoka model

$$\Delta\sigma = -\frac{e^2}{2\pi^2\hbar}\left(\Psi\left(\frac{1}{2}+\frac{B_1}{B}\right)-\frac{3}{2}\Psi\left(\frac{1}{2}+\frac{B_2}{B}\right)+\frac{1}{2}\Psi\left(\frac{1}{2}+\frac{B_3}{B}\right)\right)$$

Where Ψ is the digamma function

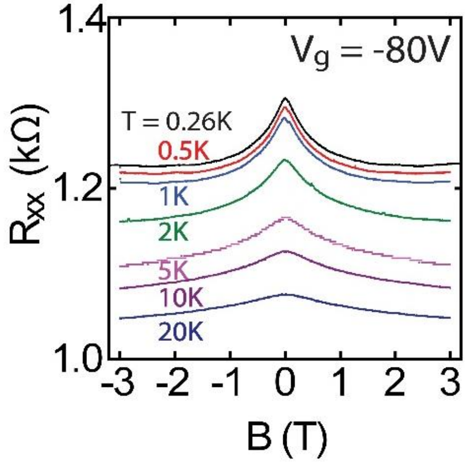
$$B_1 = B_0 + B_{so} + B_s$$

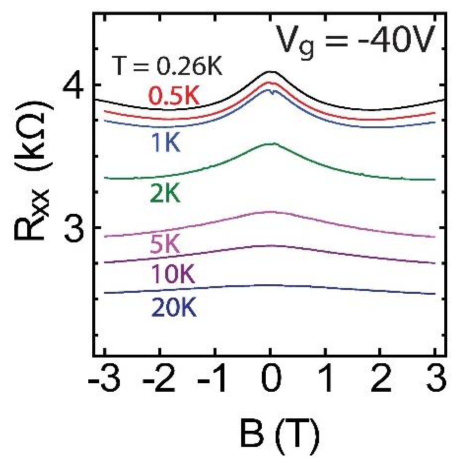
$$B_2 = \frac{4}{3}B_{so} + \frac{2}{3}B_s + B_\phi$$

$$B_3 = 2B_s + B_\phi$$

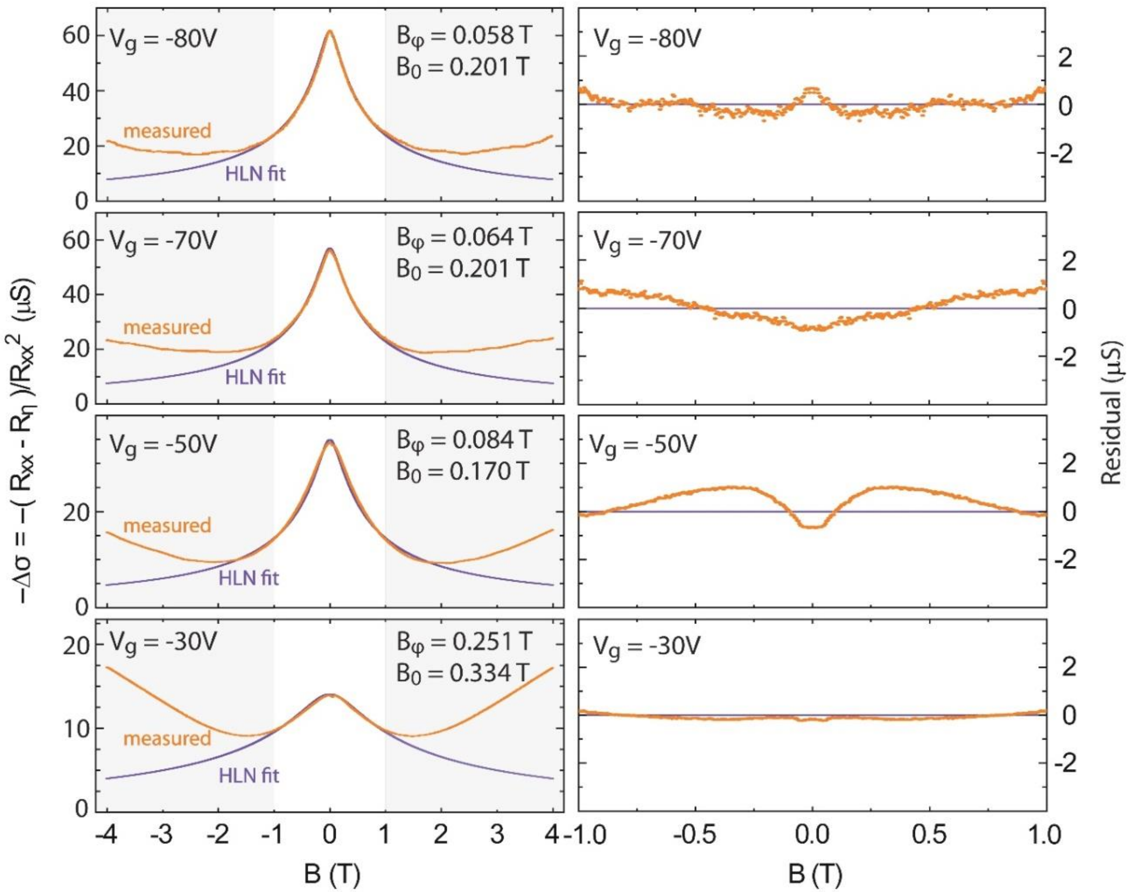
S. Hikami, A. I. Larkin, and Y. Nagaoka,
Prog. Of Theor. Phys. 63 (1980) 707.

Weak Localization





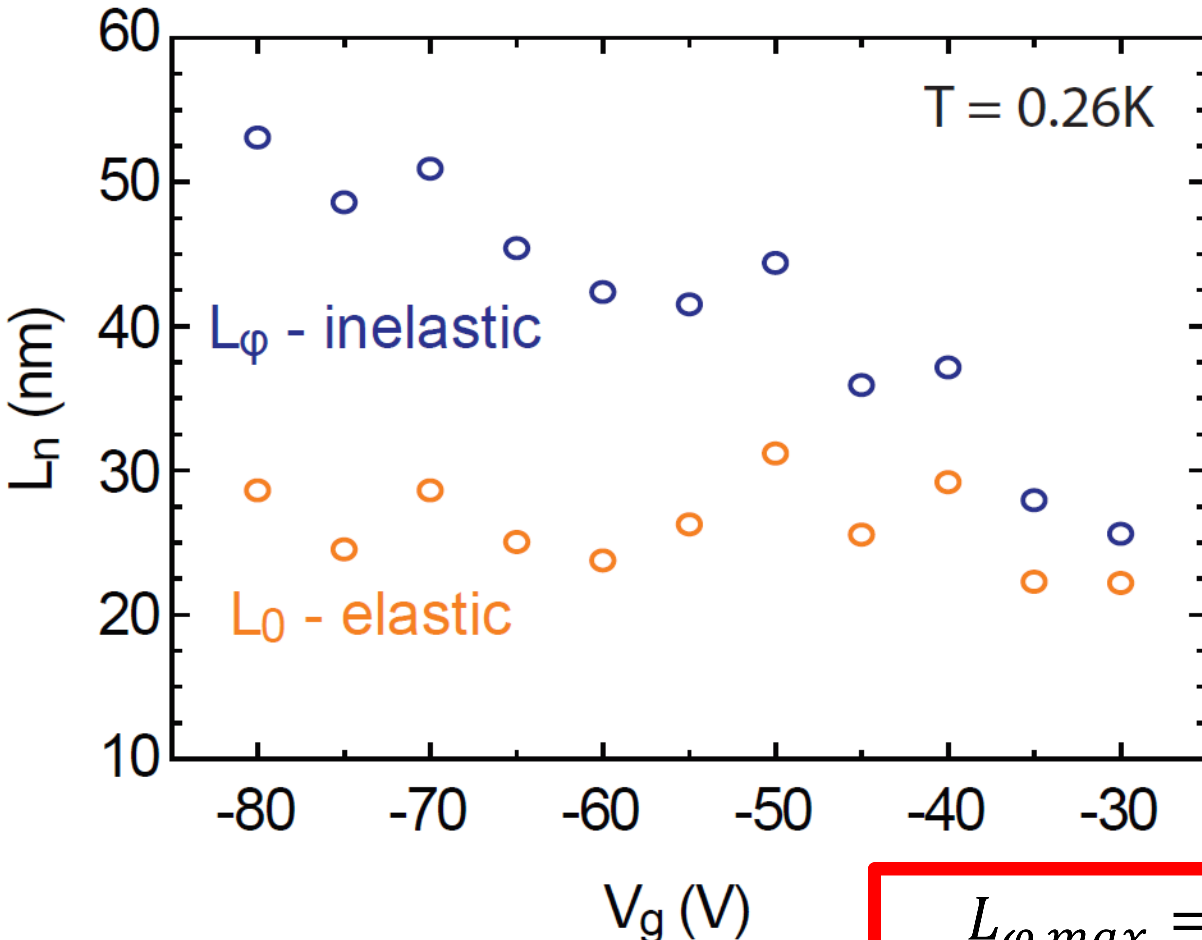
T = 0.26 K



N.Hemsworth et al, PRB 94, 245404, (2016)

Scattering Lengths

$BL^2 = {}^{h}/_{4e}$



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

N.Hemsworth et al, PRB 94, 245404, (2016)

Scattering Lengths

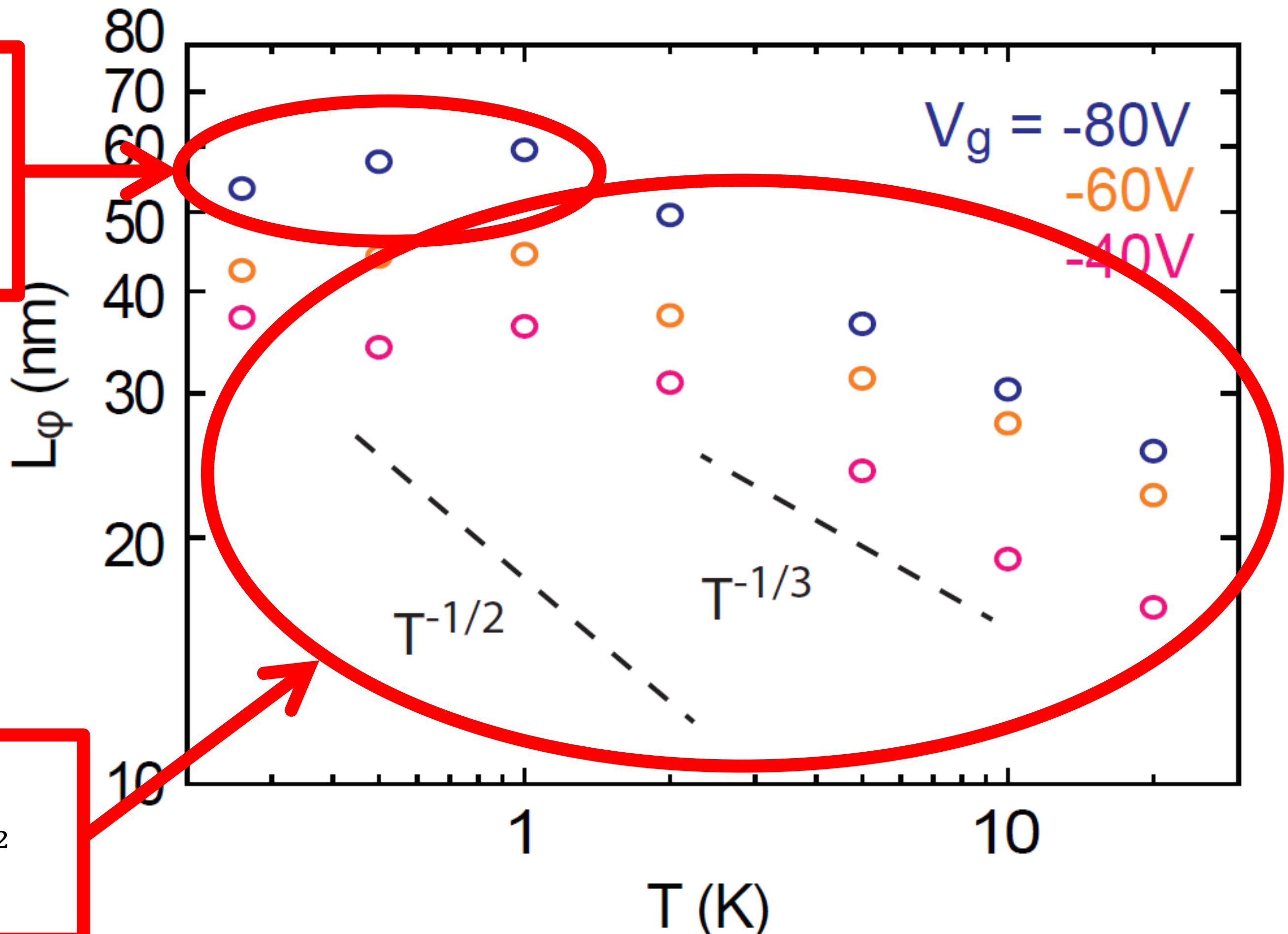
- Dephasing length vs. inelastic scattering time: $L_\varphi = \sqrt{D\tau_\varphi}$ with *D* diffusion coefficient
- Ballistic transport: $\tau_\varphi \propto T^{-2}$ or $L_\varphi \propto T^{-1}$
- Diffusive transport ($L_0 < L_\varphi$):

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

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

Scattering Lengths

Saturation most likely due to impurities.



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

N.Hemsworth et al, PRB 94, 245404, (2016)

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Qasi-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

J. Appenzeller, R. Martel, and Ph. Avouris
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):

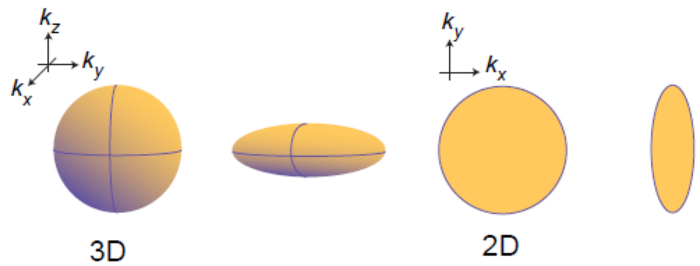
quasi-1D:

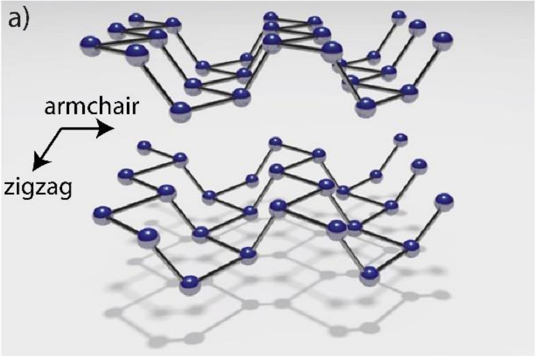
$L_\varphi, L_T > w, t$

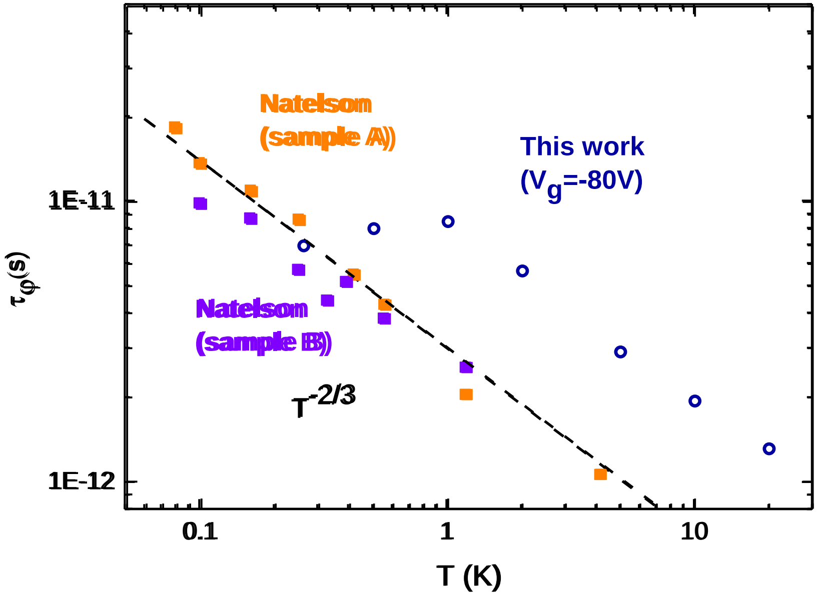
width w
thickness t

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

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







$L_\varphi = 55\ nm$

thermal length:

$L_T = \sqrt{\hbar D / k_B T}$

= 10 – 60 nm

N.Hemsworth et al, PRB 94, 245404, (2016)

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Conclusions...

- ✓Weak localization oberved in a bP FET
- ✓Excellent agreement with HLN model
- ✓Dephasing length L_φ reaches 55 nm
- ✓T-dependence of L_φ close to quasi-1D
- ✓This is a further proof of strong in plane anisotropy of bP

N.Hemsworth, et al, PRB 94, 245404, (2016)

...and outlooks

SEED Project
SURface properties of few layer black PHOSphorus investigated by scanning tunnelling microscopy

- Clean surface of few-layer bP
  - On graphene on SiC
  - On Si/SiO_2
- Study of point defects
- Functionalization of the surface by metal evaporation

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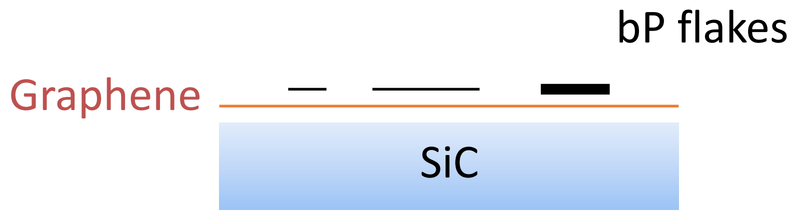
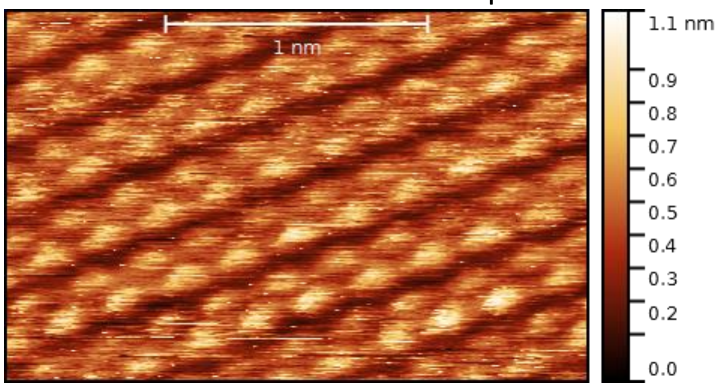
... and outlooks



Ongoing activity: **Atomic Resolution on few-layer bP**

Measured at room temperature



Measured unit cell parameter

a = 3.86 Å, c = 4.27 Å

Measured parameters are in very close agreement to the reported and predicted values

C. D. Zhang et. al. J. Phys. Chem. C 2009, 113, 18823.
Morita, A et. al. Appl. Phys. A: Mater. Sci. Proc. 1986, 39, 227.

T= 4.3K

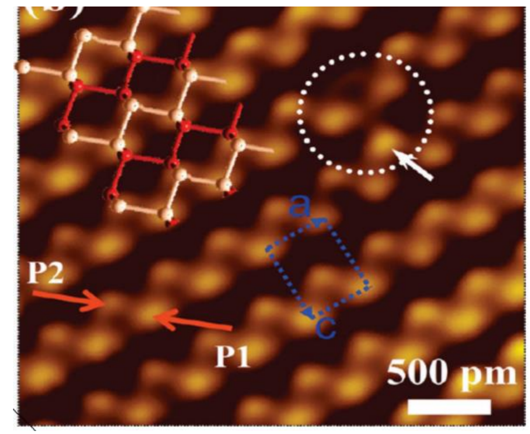


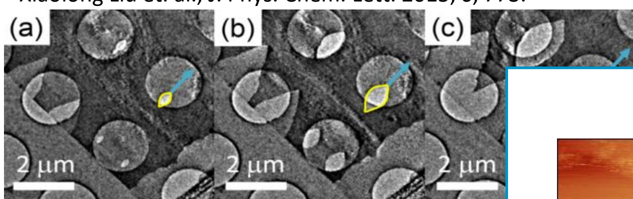
TABLE 1: Measured Surface Lattice Constants and Theoretical Optimized Results Together with Previous Data of Bulk BP

reported by Morita[7]	measured from STM images	theoretical optimized results
$a = 3.313$ Å	$a = 3.33$ Å	$a = 3.28$ Å
$b = 10.473$ Å		$b = 10.37$ Å
$c = 4.374$ Å	$c = 4.33$ Å	$c = 4.35$ Å
$d_1 = 2.222$ Å, $\alpha_1 = 96.5°$		
$d_2 = 2.777$ Å, $\alpha_2 = 101.9°$		

... and outlooks

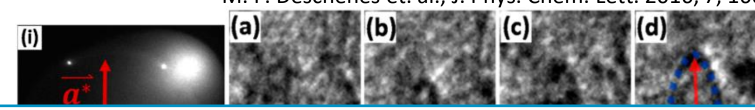
Ongoing activity: **Controlled desorption of bP**

Xiaolong Liu et. al., J. Phys. Chem. Lett. 2015, 6, 773.

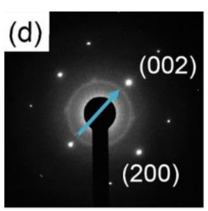


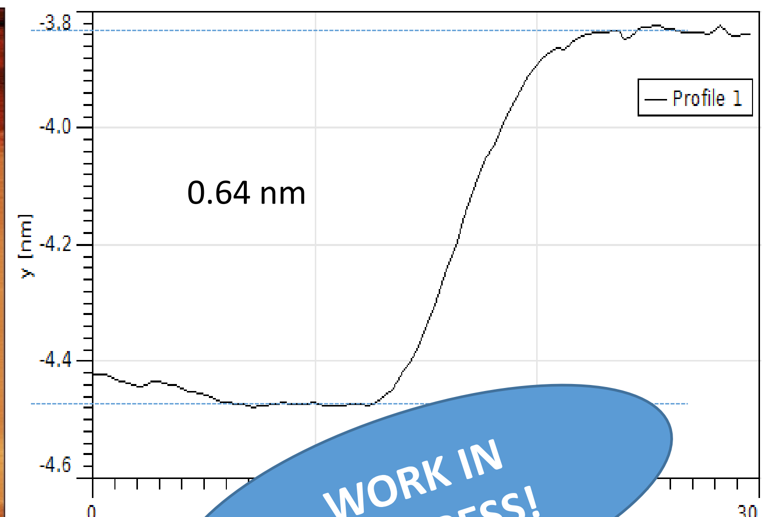
TEM image of eye shaped crack opening o
bP flake at 400°C for 5, 8 and 12 min.

M. F. Deschenes et. al., J. Phys. Chem. Lett. 2016, 7, 1667.



- decomposition of 2D BP is obse occur at ~400 °C in vacuum, in contrast to the 550 °C bulk BP sublimation temperature
- This decomposition initiates via shaped cracks along the [001] d





WORK IN PROGRESS!

After 2h anealing at 400°C

... and outlooks

SEED Project

SURface properties of few layer black PHOSphorus investigated by scanning tunnelling microscopy

F. Telesio

A. Kumar

S.Heun

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M. Peruzzini

*“**Phos**phorene **fun**ctionalization: a new platform for advanced multifunctional materials”*

Thank you for your attention!

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