Black Phosphorus Field Effect Transistors: Passivation By Oxidation, and the Role of Anisotropy in Magnetotransport

Tomasz Szkopek

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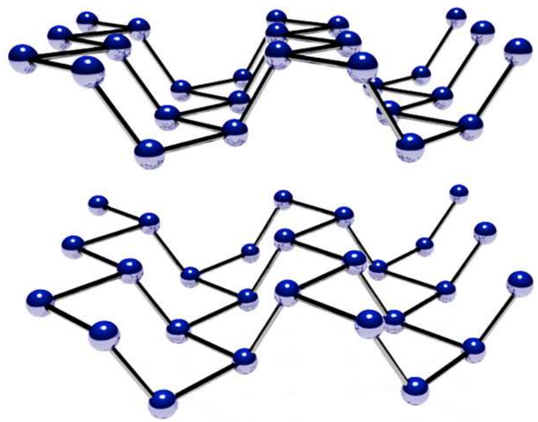
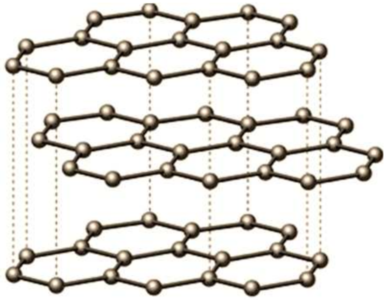
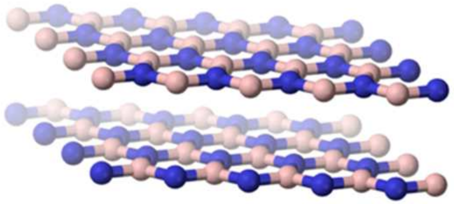
Electrical and Computer Engineering, Physics



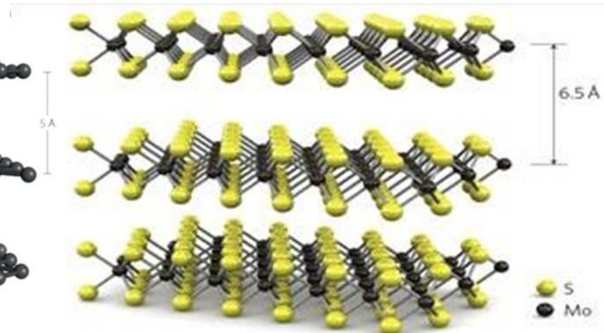
231st ECS Meeting, 1 June 2017
New Orleans

layered materials

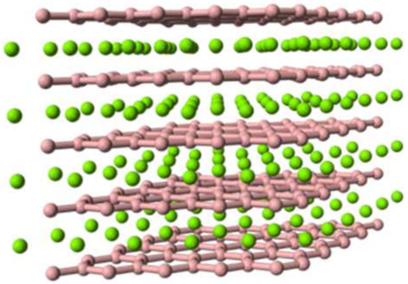

C (graphite)

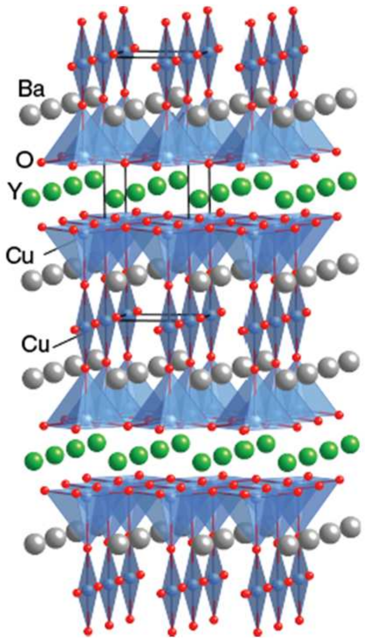

BN (white graphite)


P (black-P)

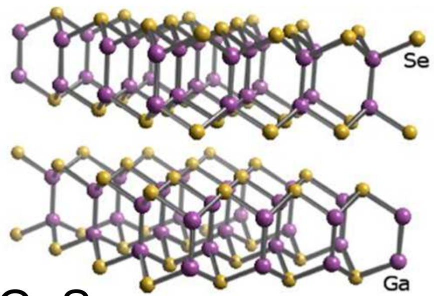


MoS_2 (transition metal dichalcogenide)

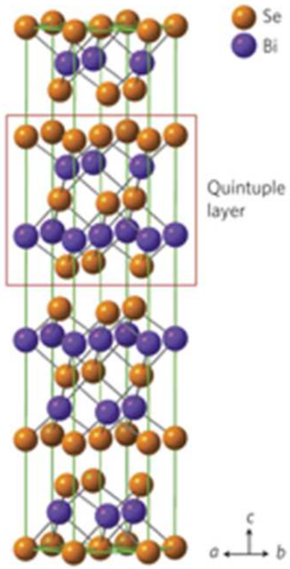

MgB_2



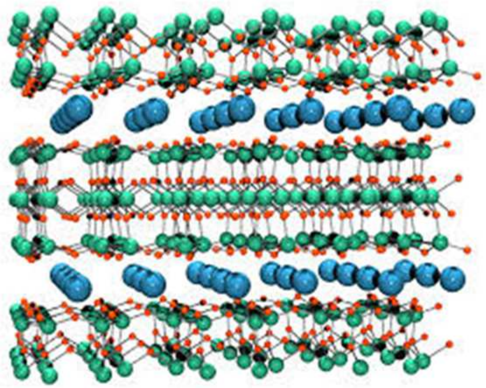
$YBa_2Cu_3O_{7-x}$ (high-T_c cuprate)

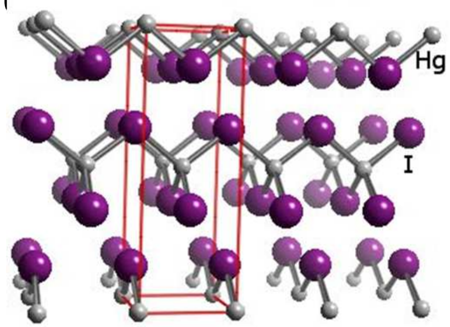


GaSe (group III monochalcogenide)



Bi_2Se_3 (sesquichalcogenide)


$KAl_2(AlSi_3O_{10})(OH)_2$ (mica)



HgI_2 (transition metal halide)

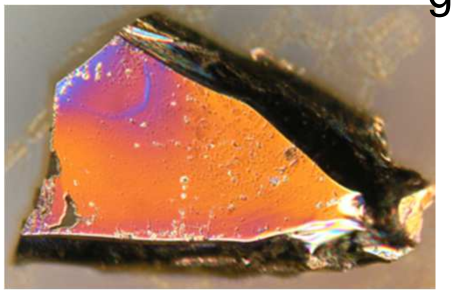
layered materials

C (graphite)

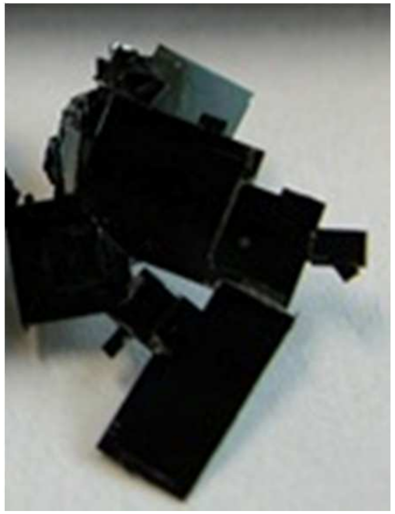
BN (white graphite)

P (black-P)

MoS_2 (transition metal dichalcogenide)



MgB_2



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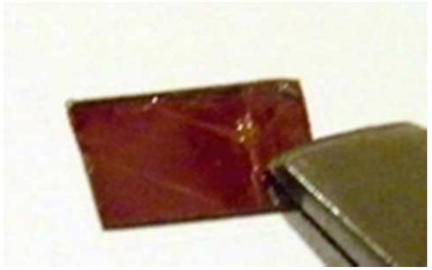

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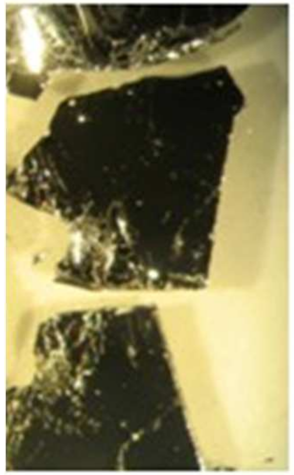
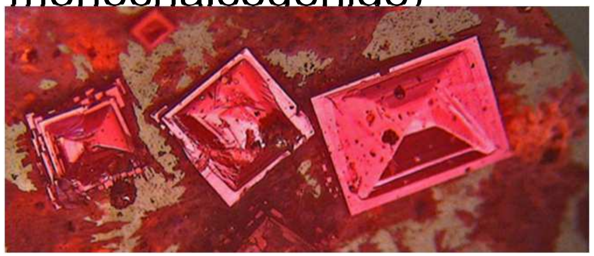


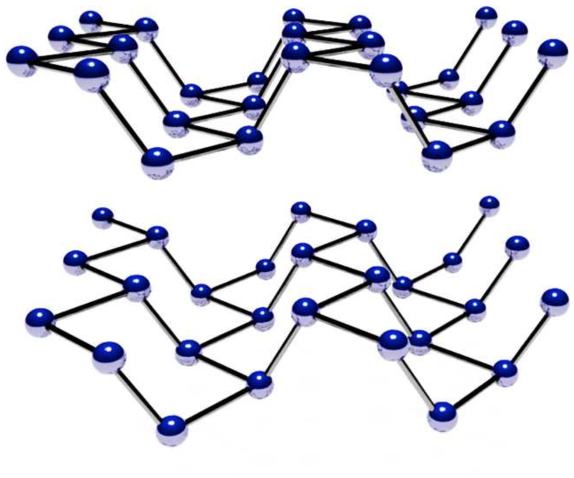
Bi_2Se_3 (sesquichalcogenide)

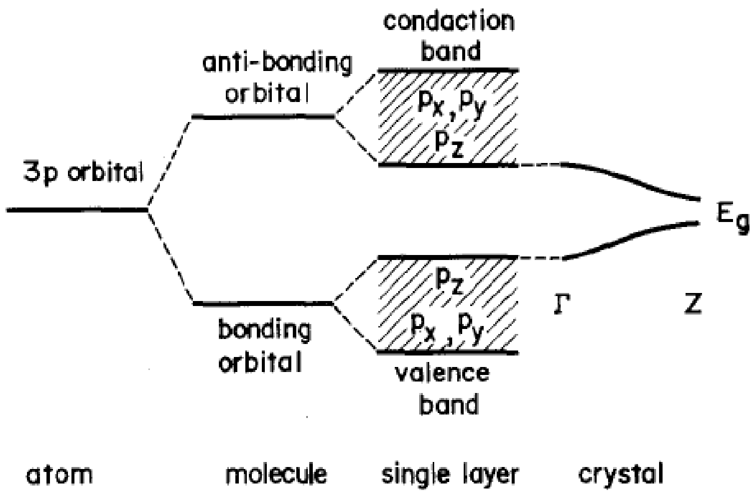
$KAl_2(AlSi_3O_{10})(OH)_2$ (mica)



HgI_2 (transition metal halide)

black phosphorus (bP)





1914: Bridgman produces first bP

1953: Keyes studies bP as a semiconductor

1968: Berman & Brandt; Witting & Mattias observe superconductivity at high pressure

1970's - **1980's**: burst of activity in Japan on electronic properties, Raman, cyclotron resonance

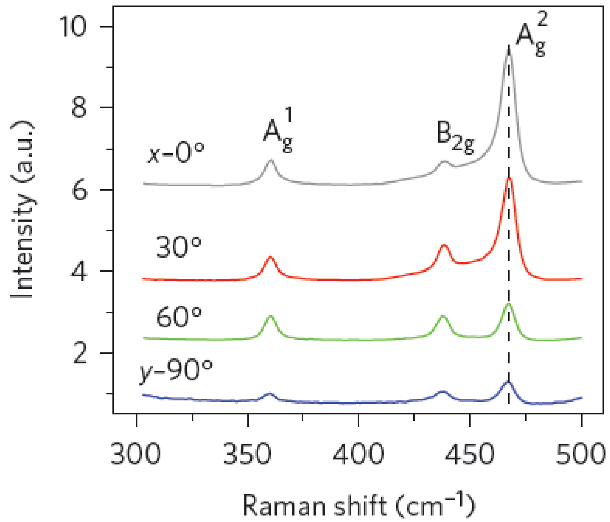
2014: ultra-thin bP FETs reported by Yuanbo Zhang (Fudan) and Peide Ye (Purdue)

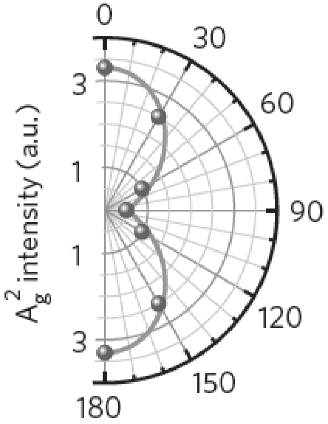
bulk band gap = 0.3 eV

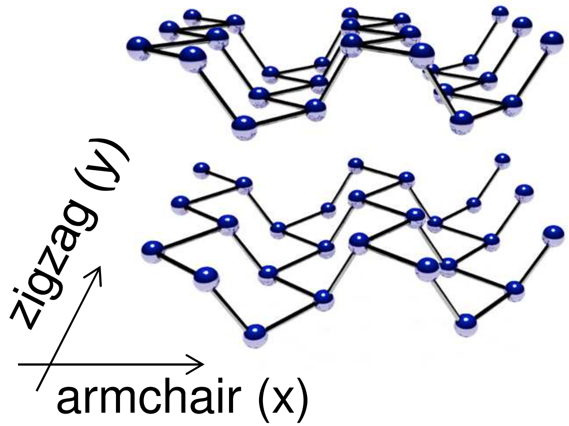
monolayer band gap ≈ 1.2 eV

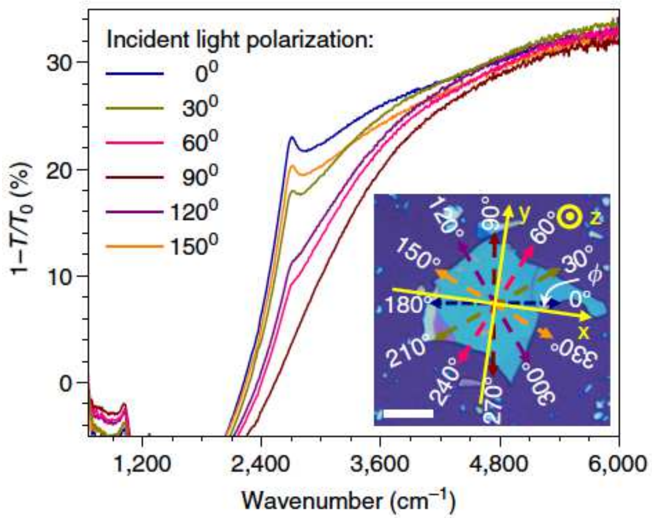
A. Morita, "Semiconducting Black Phosphorus", Appl. Phys. **A39**, 227 (1986).

bP anisotropy









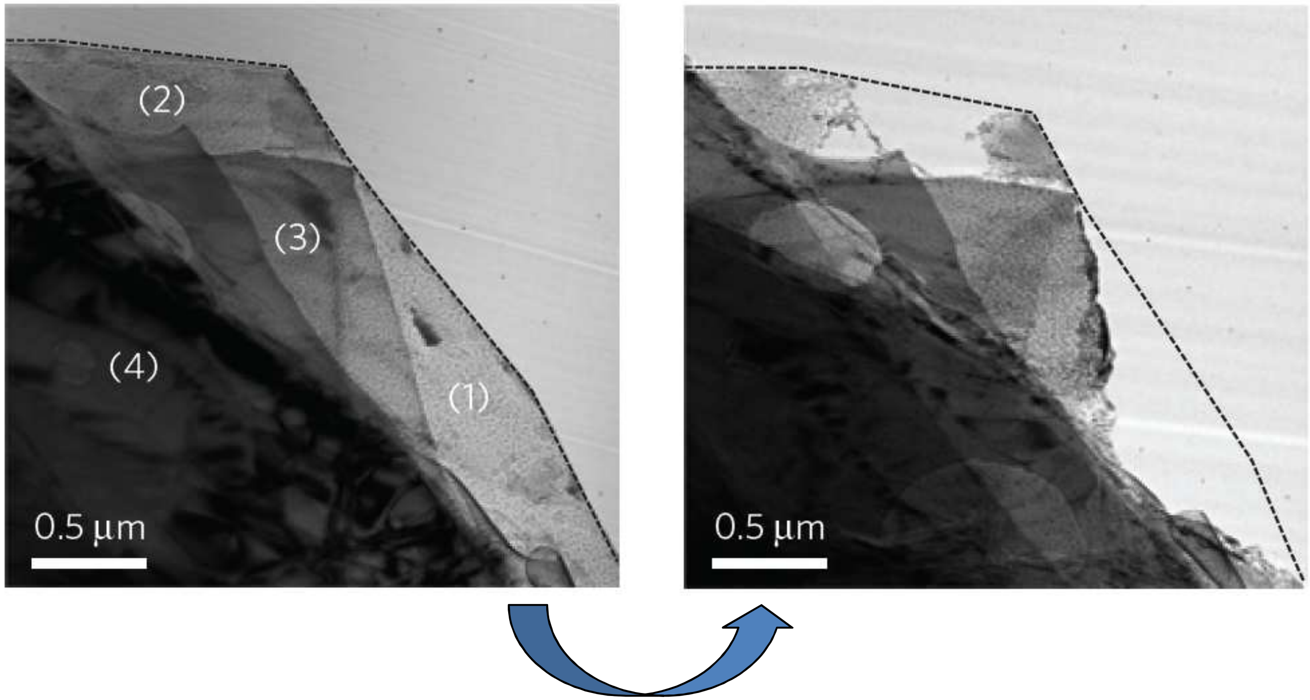
Fengnian Xia…, Nature Comm. 2014, Nature Comm. 2015.

cyclotron effective mass

	m_x	m_y	m_z
electron	0.083	1.027	0.128
hole	0.076	0.648	0.280

S. Narita, et al. J. Phys. Soc. Jpn. **52**, 3544 (1983)

bP photo-oxidation



20s exposure to ambient air + light

Rapid bP photo-oxidation with combination of O_2, H_2O and light

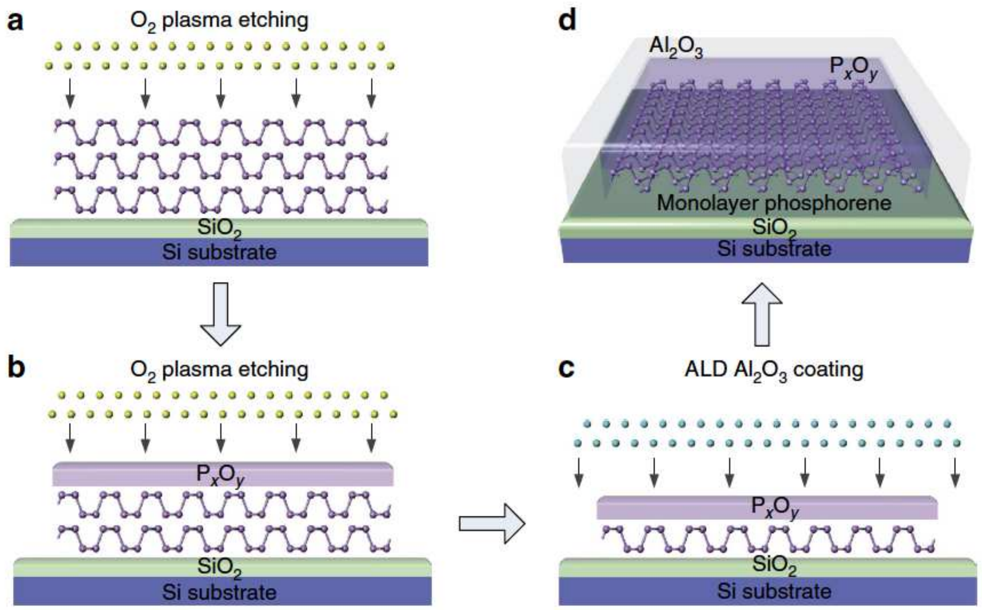
A. Favron …. R. Martel, Nature Materials, 2015

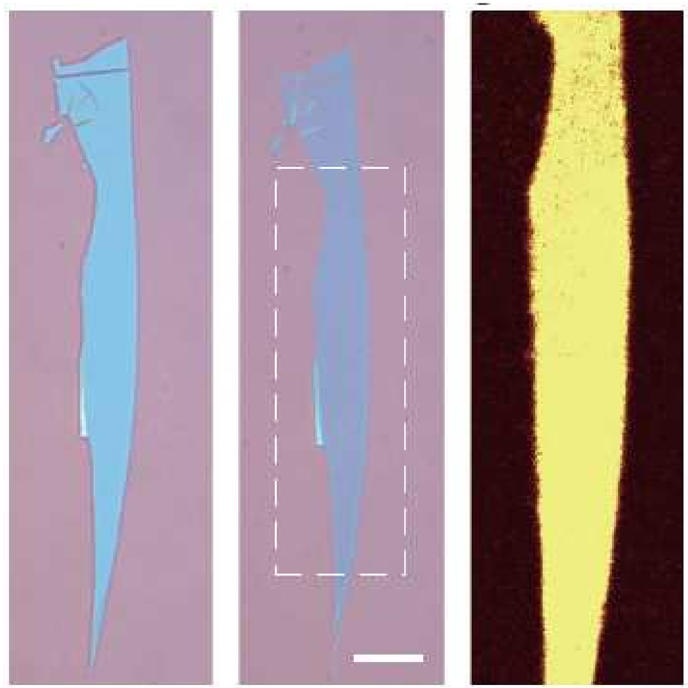
outline

- oxidation for top-gated field effect transistors
- weak-localization & magnetorsistance and anisotropy

manuscript in preparation

oxidation for passivation and thinning





oxidation formation

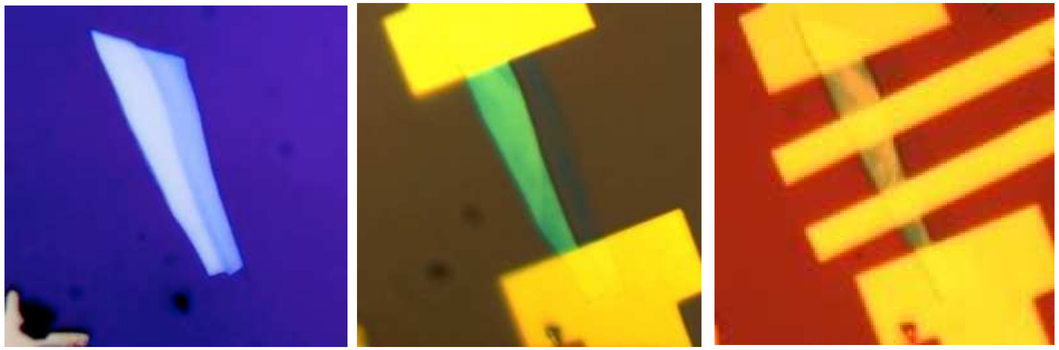
microscopy

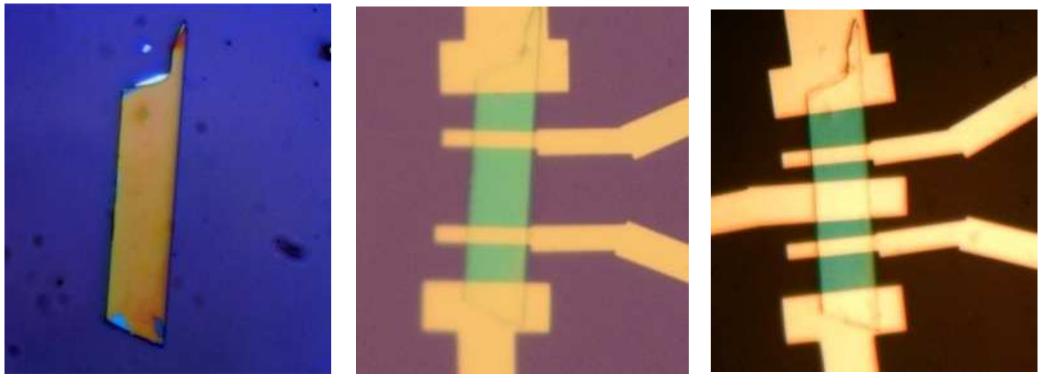
PL

PL efficiency is preserved. Can oxidation be used for gate dielectrics?

Jiajie Pei, Xin Gai, … B. Luther Davies, Yurei Liu, Nature Comm., 2015.

bP FET fabrication





bulk bP source:
>99.9% purity

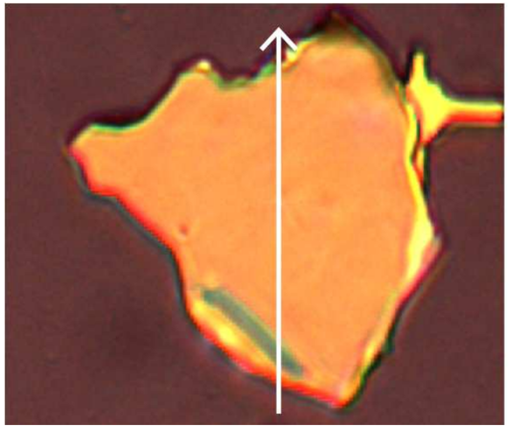
exfoliation & processing in glove box
O_2, H_2O < 1ppm

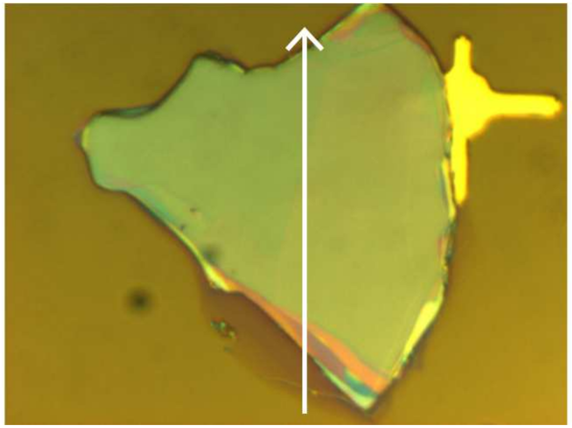
e-beam lithography, Ti/Au contacts

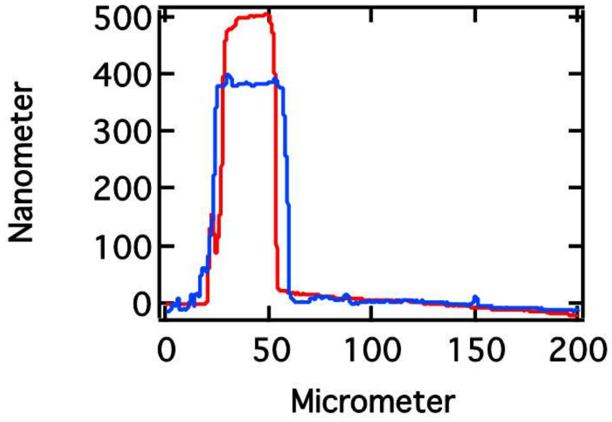
oxidation: 200 mTorr, 300 W RF, 1-3 minutes

e-beam lithography, Ti/Au top gates

etch rate by oxidation



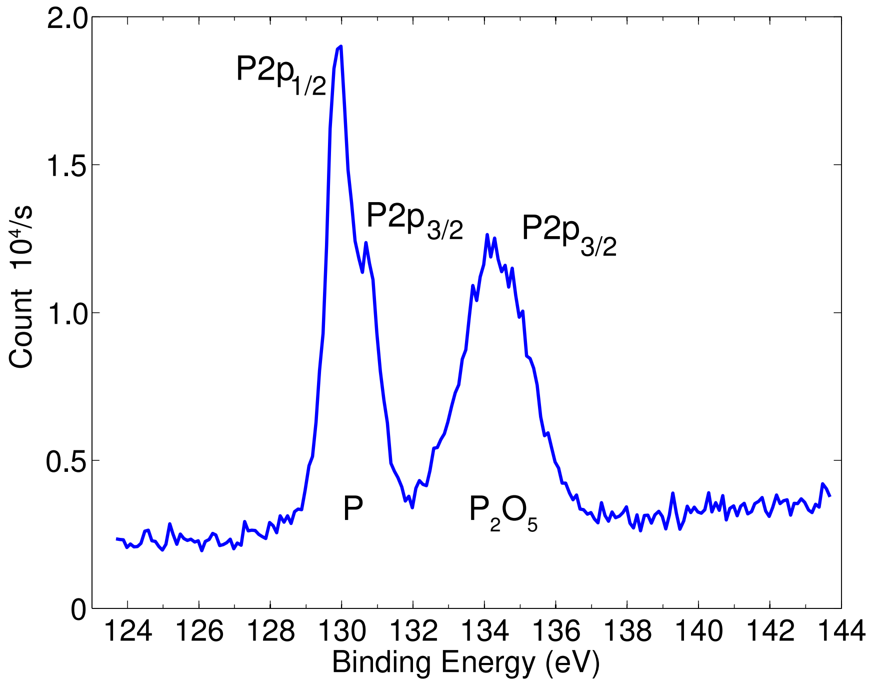


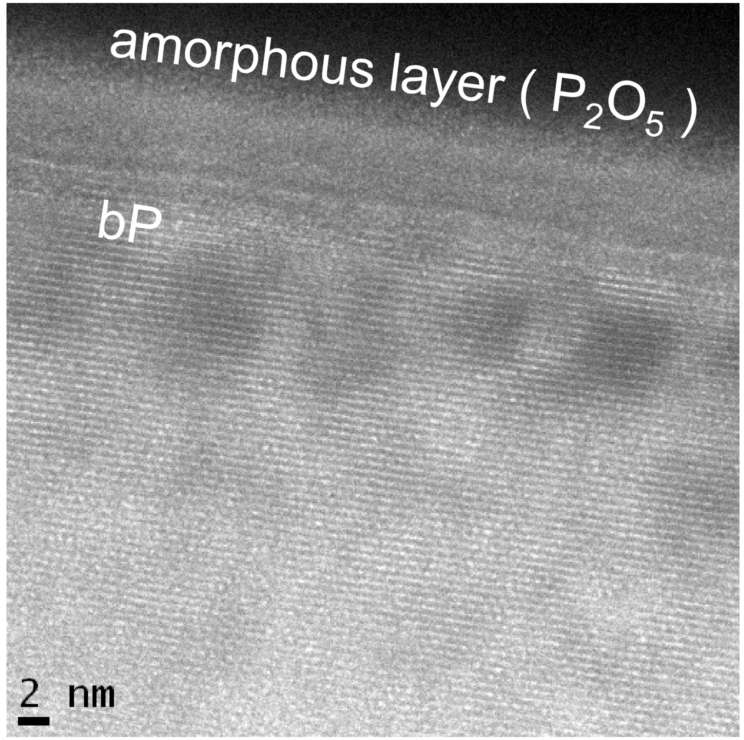


oxidation: 10sccm O_2, 200 mTorr, 300 W RF

etch rate: 0.10 nm/s or ~0.5 bP layers/s

XPS + TEM





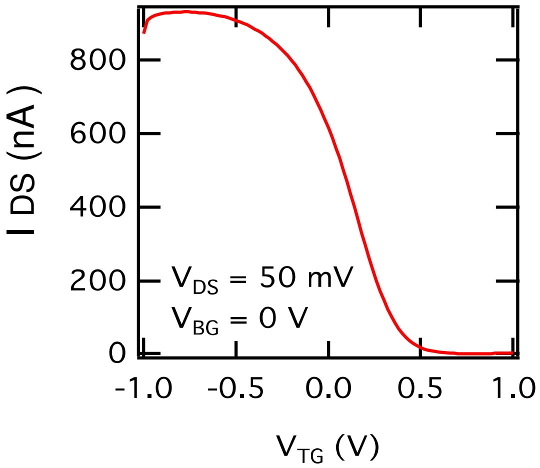
oxidation of bulk bP crystal

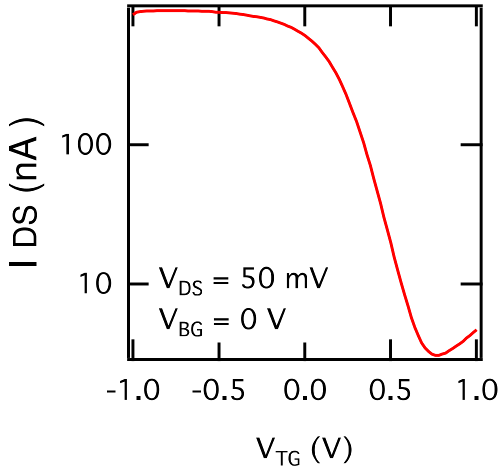
XPS: elemental P and P_2O_5 present

oxidation of bP flake on SiO_2/Si

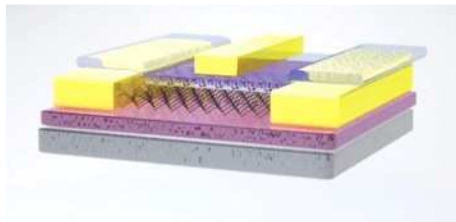
TEM: amorphous layer (< 6nm thick), interfacial roughness with bP

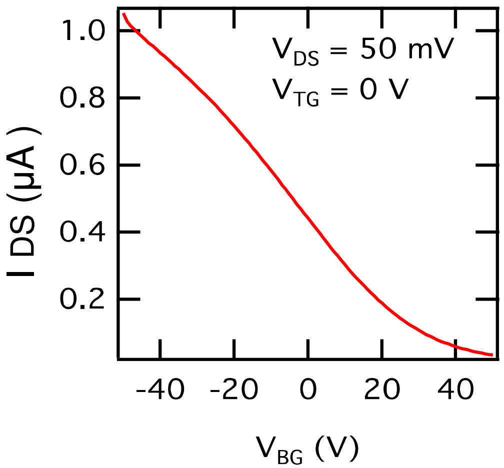
field effect

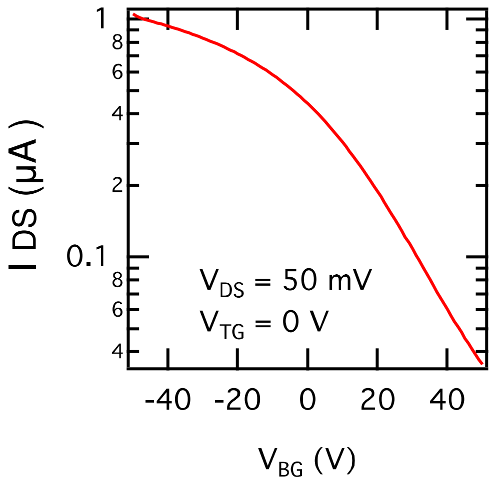




top gate modulation

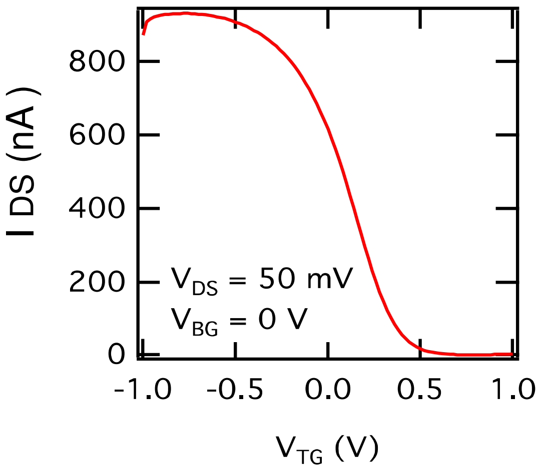


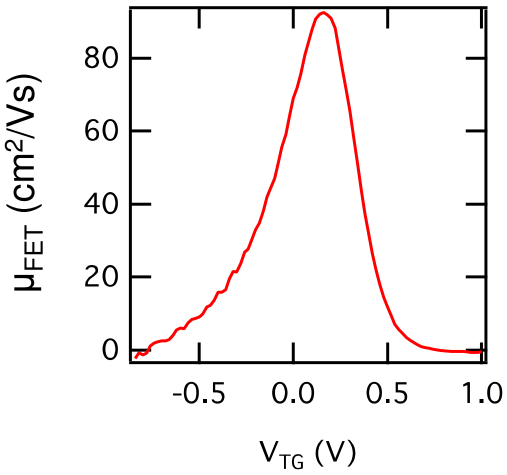




bottom gate modulation

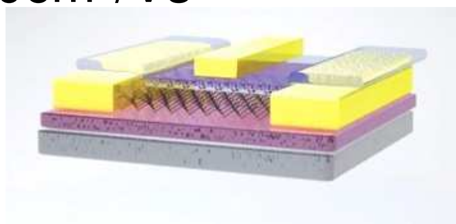
field effect mobility

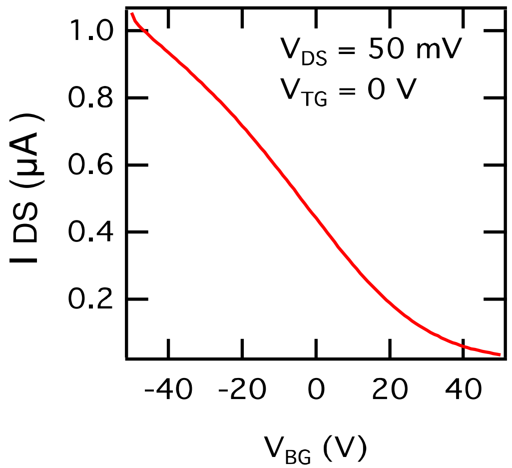


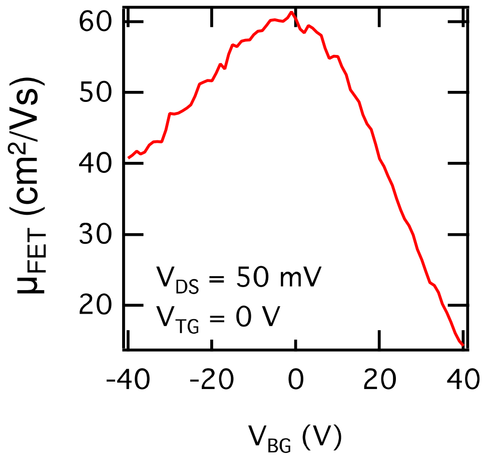


top gate modulation

peak FET mobility: $90cm^2/Vs$



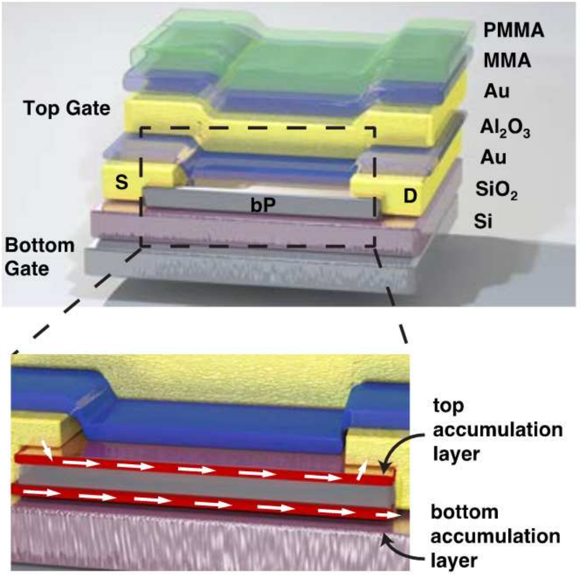


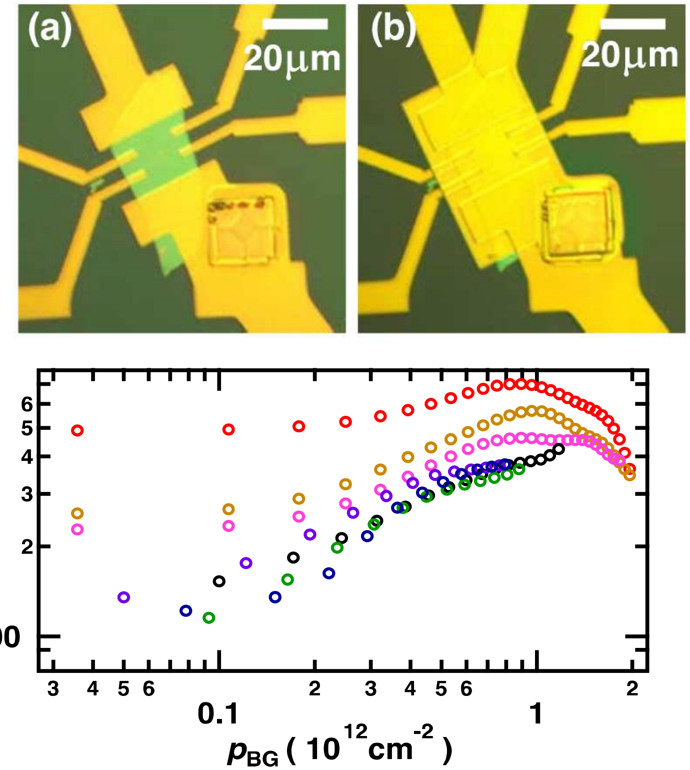


bottom gate modulation

peak FET mobility: $60cm^2/Vs$

mobility limiting mechanisms





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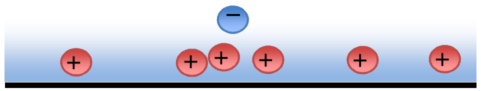
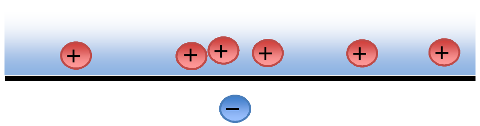
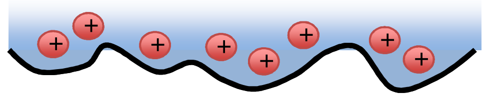


impurities



remote impurities

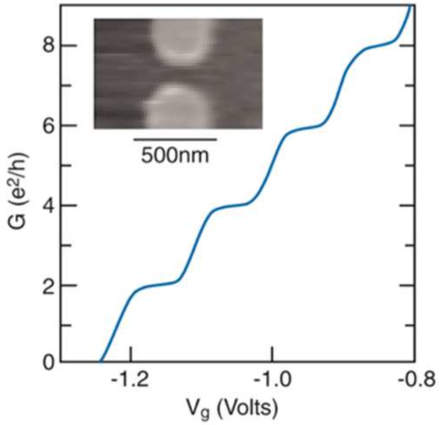


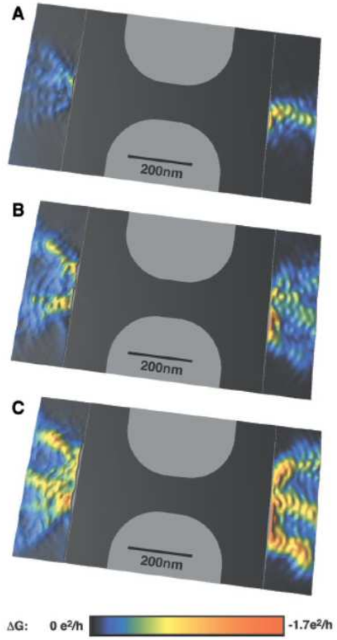
surface roughness scattering

V. Tayari et al., Phys. Rev. Applied **5**, 064004 (2016)

future: split gate transistors

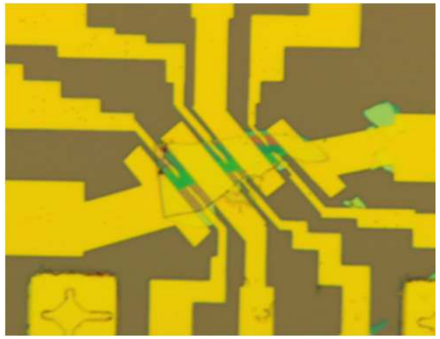
GaAs/AlGaAs quantum point contacts

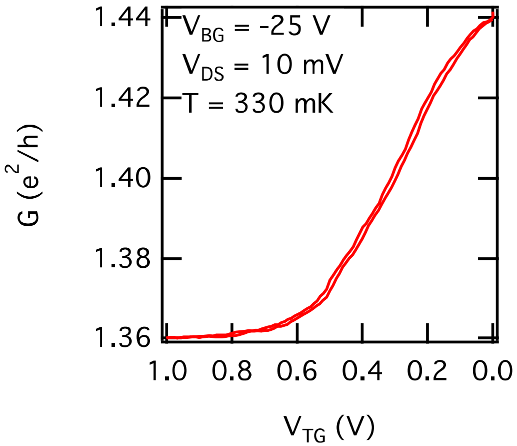




M.A. Topinka, et al., Science **289**, 2323 (2000).

bP split-gate structures



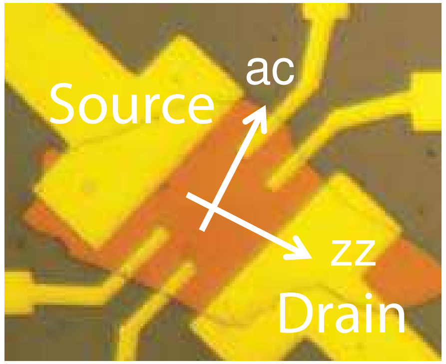


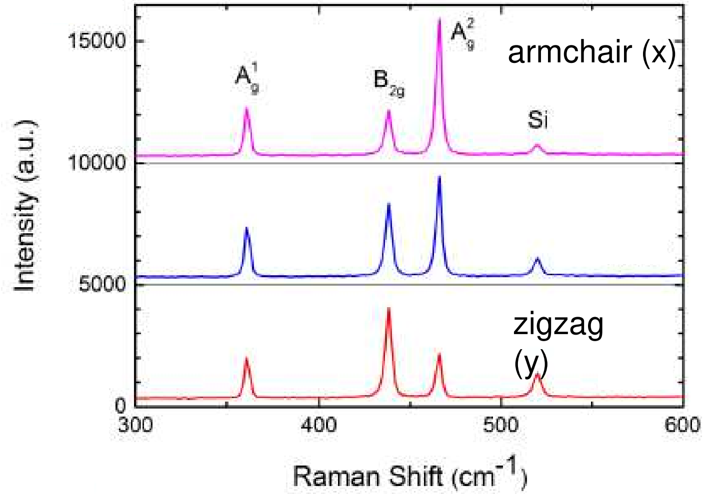
outline

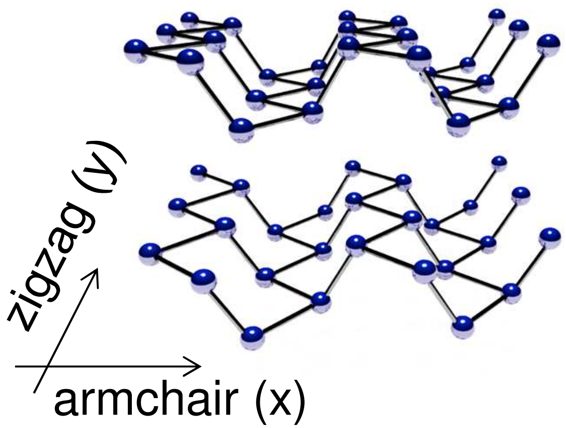
- oxidation for top-gated field effect transistors
- weak-localization & magnetorsistance and anisotropy

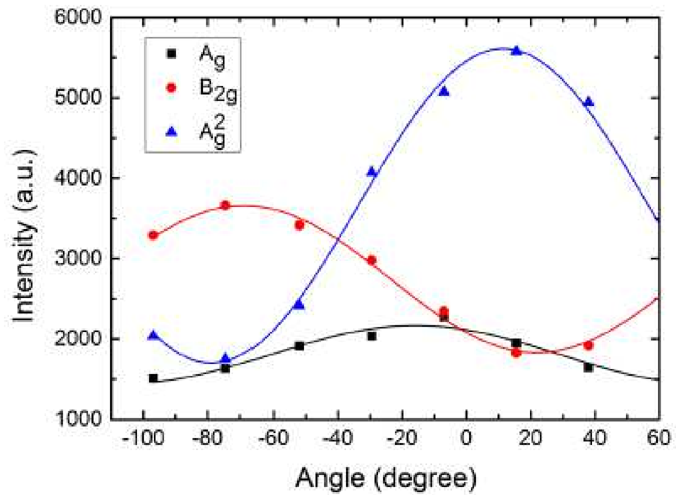
N. Hemsworth, V. Tayari, F. Telesio, S. Xiang, S. Roddaro, M. Caporali, A. Ienco, M. Serrano-Ruiz, M. Peruzzini, G. Gervais, T. Szkopek, and S. Heun, Dephasing in strongly anisotropic black phosphorus, Phys. Rev. B ***94****, 245404 (2016).*

anisotropy : Raman spectroscopy

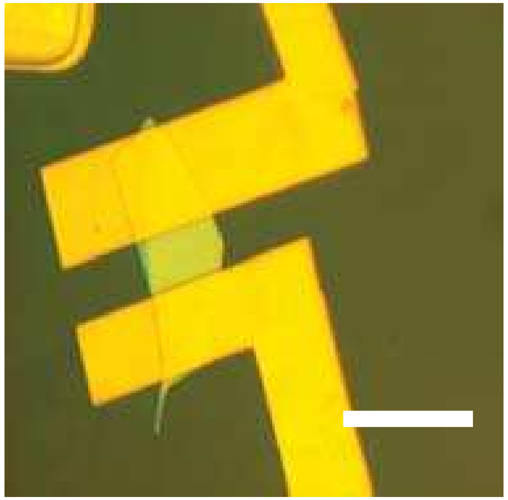


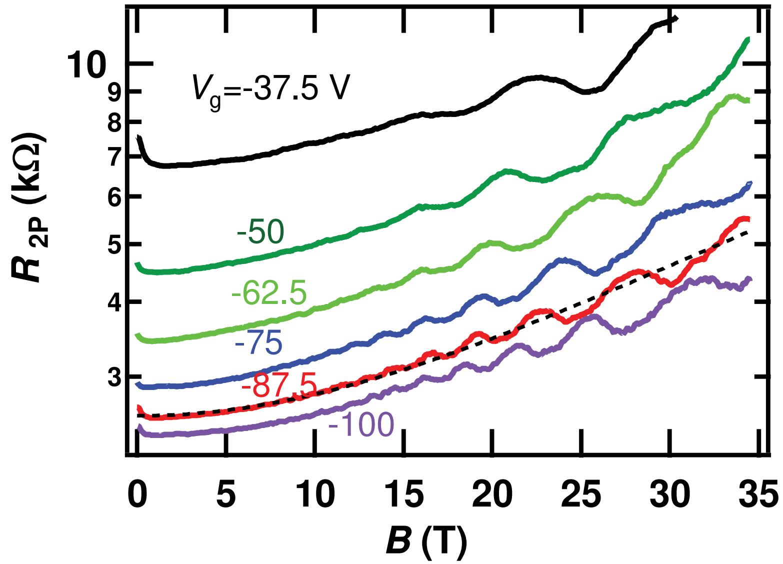


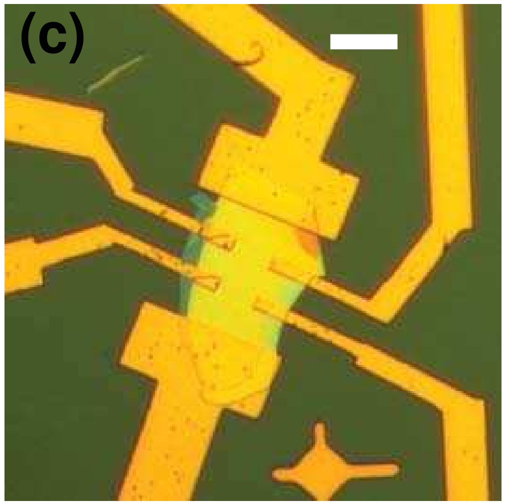


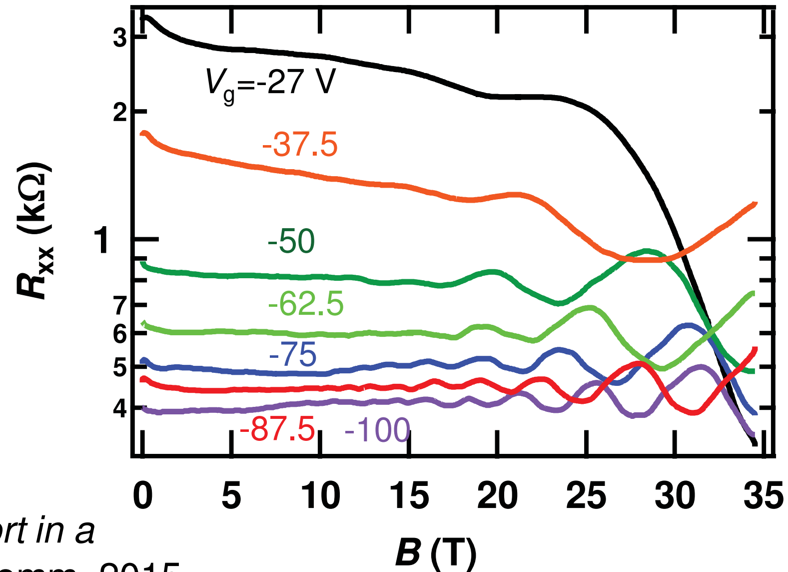


magnetoresistance



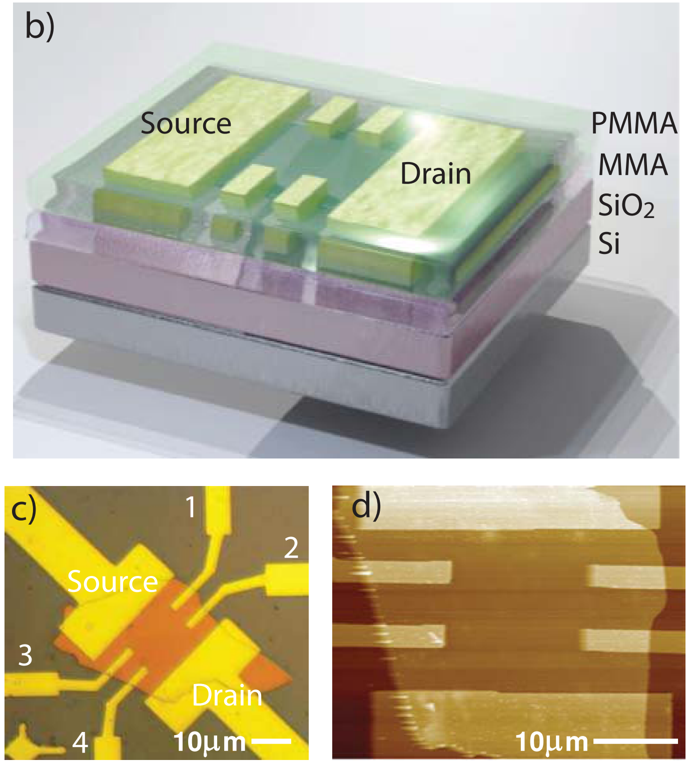


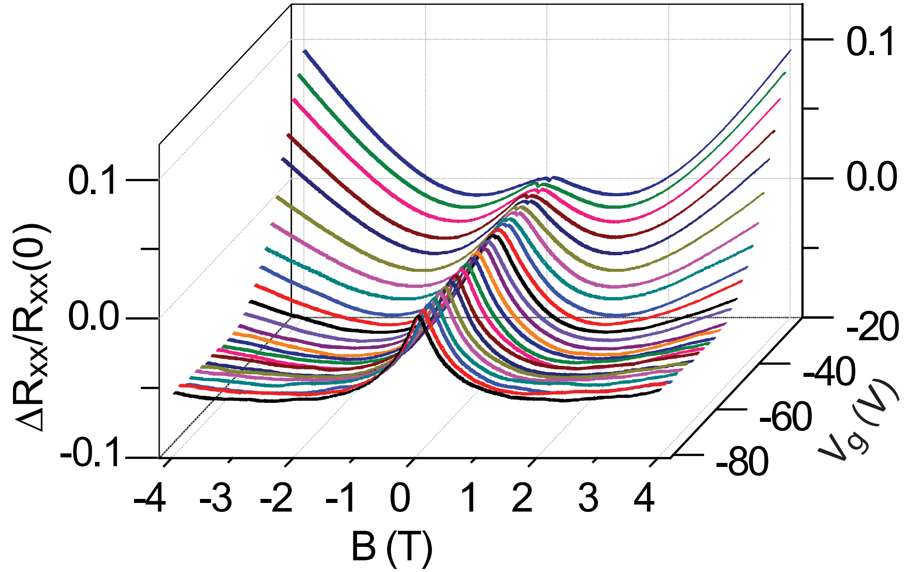


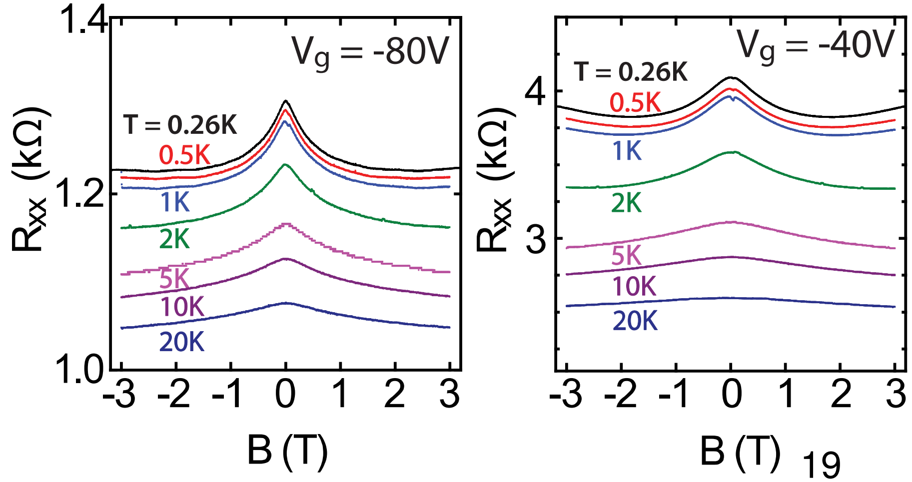


V. Tayari et al., *Two dimensional magnetotransport in a naked black phosphorus quantum well*, Nature Comm. 2015.

weak localization



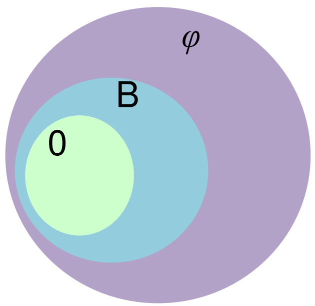


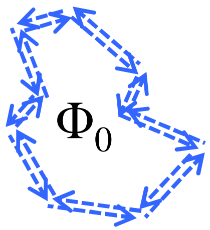


weak localization – fit with theory

$$\Delta\sigma(B) = -\frac{e^2}{2\pi^2 h}\left[\Psi\left(\frac{1}{2}+\frac{B_0}{B}\right)-\Psi\left(\frac{1}{2}+\frac{B_\varphi}{B}\right)\right]$$

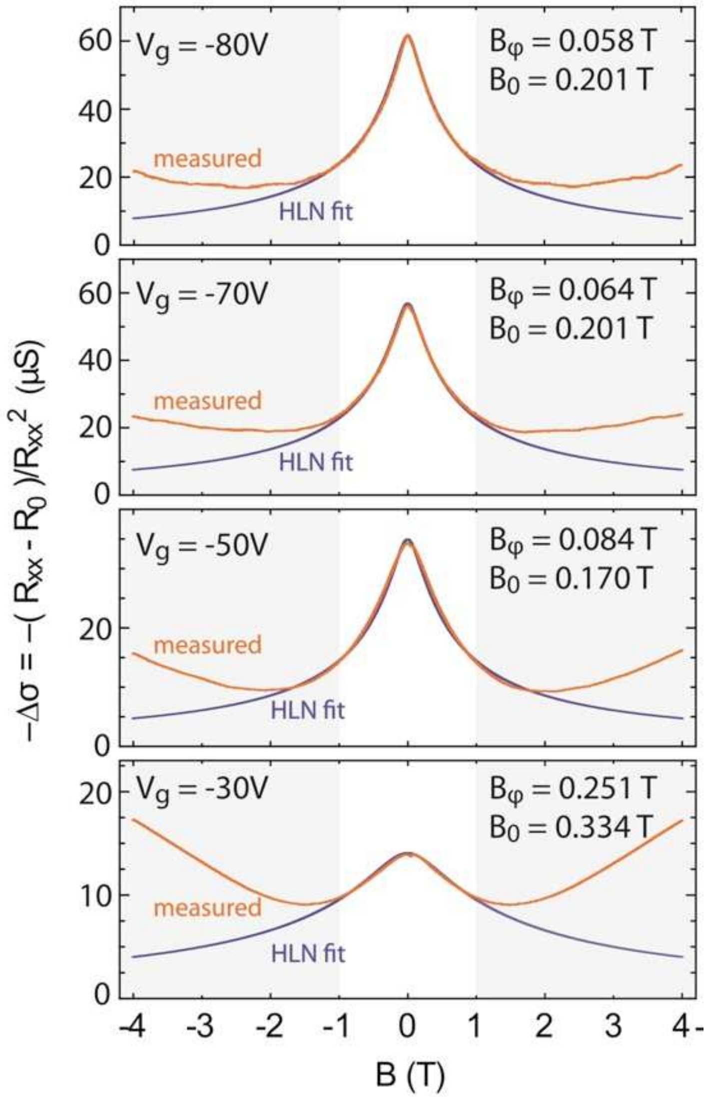
$\Psi(x)$ = digamma function





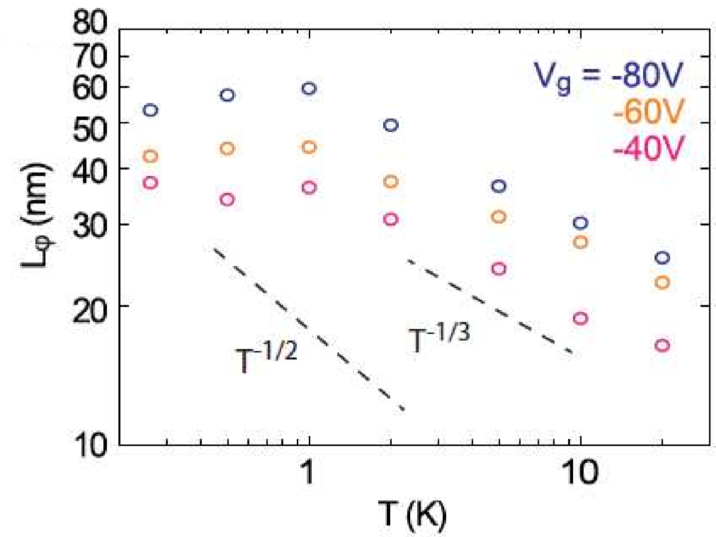
elastic scattering length: $_0 = \sqrt{D\tau_0}$

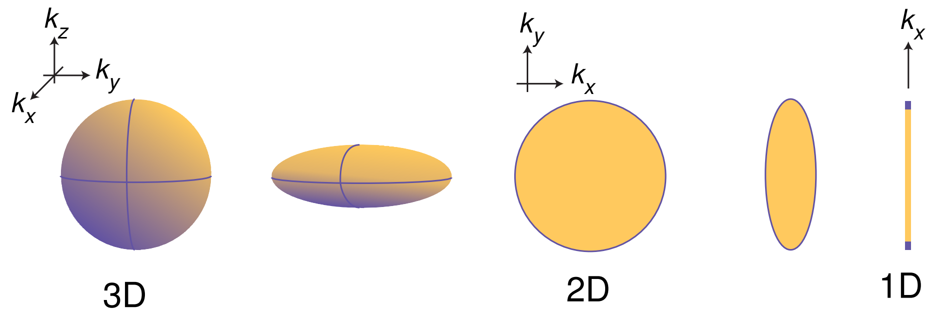
inelastic scattering length: $_\varphi = \sqrt{D\tau_\varphi}$



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

localization & anisotropy

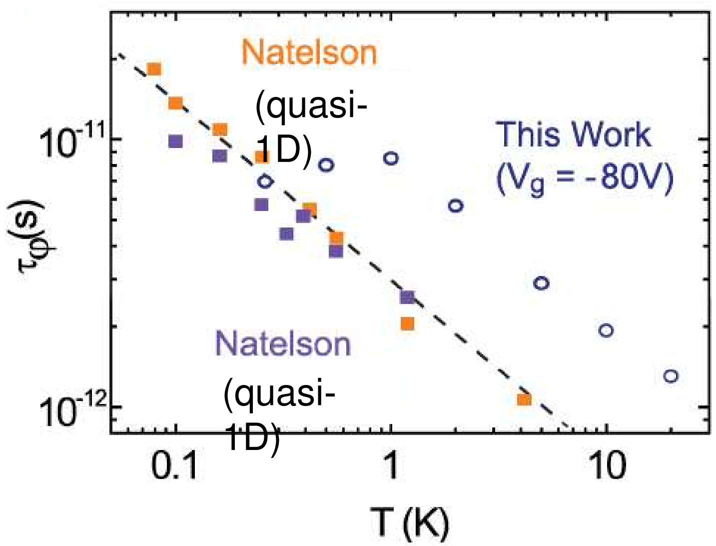




Electron-electron scattering in a diffusive 2D conductor: $_{\varphi} \propto T^{-1/2}$

$$\tau_\varphi = T^{-1}$$

Altshuler, Khmelnitzkii, Larkin, Lee, PRB (1980).
Abrahams, Anderson, Lee, and Ramakrishnan, PRB (1981).

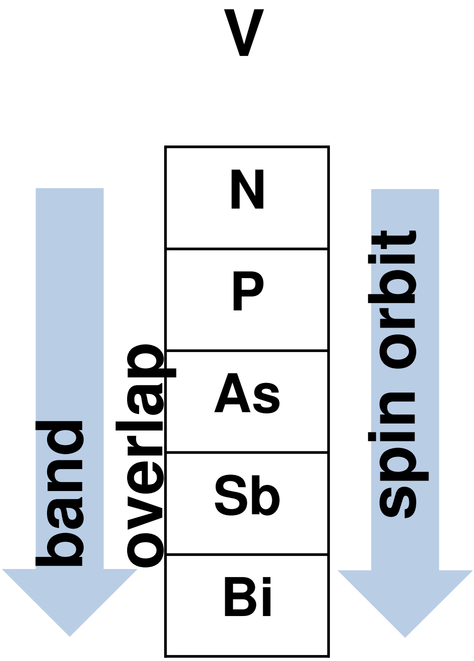


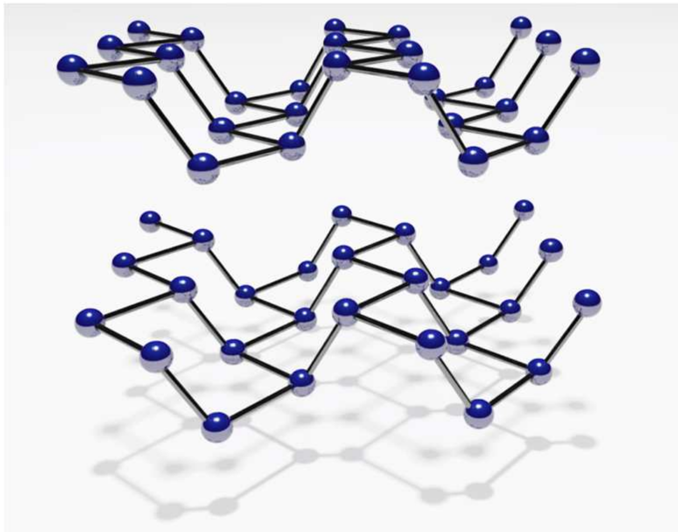
Electron-electron scattering in a diffusive 1D conductor: $_{\varphi} \propto T^{-1/3}$

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

Appenzeller, Martel, Avouris, Stahl, Hunger, Lengeler, PRB (2001).
Natelson, Willett, West, and Pfeiffer, PRL (2001).

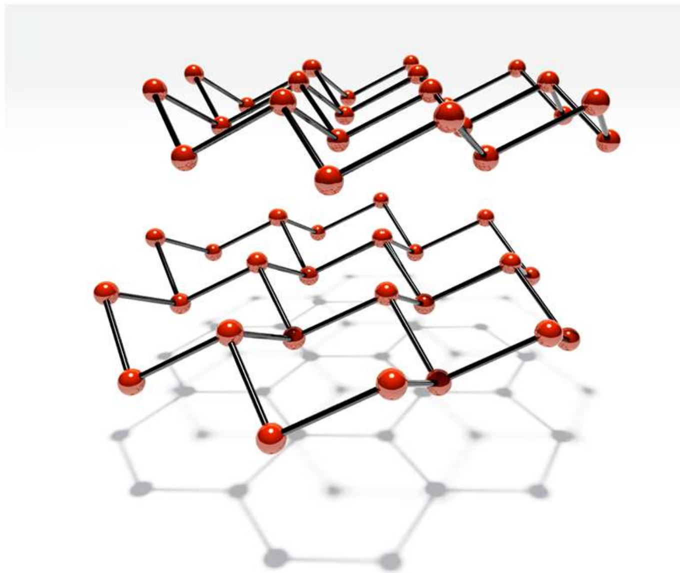
future: pnictogens





P :

puckered honeycomb



As, Sb, Bi :

buckled honeycomb

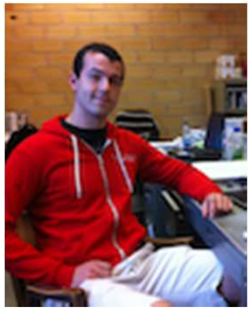
the team

Vahid Tayari

Francesca Telesio

Maurizio Peruzzini Firenze

Stefan Heun Pisa



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thank you