(Suppression of) Dephasing in a Field-Effect Black Phosphorus Transistor

Guillaume Gervais (Physics) and Thomas Szkopek (Electrical Eng.)

McGill

July 28, 2016

This talk contains no quantum Hall effect at a☹.

Due Credit for Black Phosphorus FETs

The Device-maker boss: **Prof. Thomas Szkopek**, McGill Electr. Engineering

CNR-Florence, Italy: M. Caporali, A. Ienco, M. Serrano-Ruiz, M. Perruzin
(material synthesis)

Scuola Normale Pisa: *Dr. Heun*, F. Telesio, S.Xiang, S. Roddaro (weak localization)

+

a little army of “one” @ McGill

Vahid Tayari

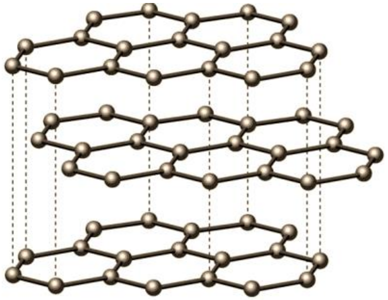
Nick Hemsworth

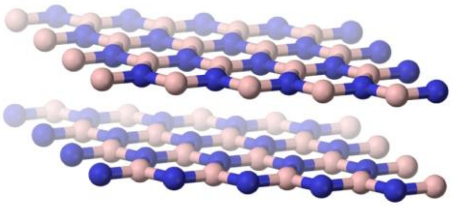
Ibrahim Fakih

McGill

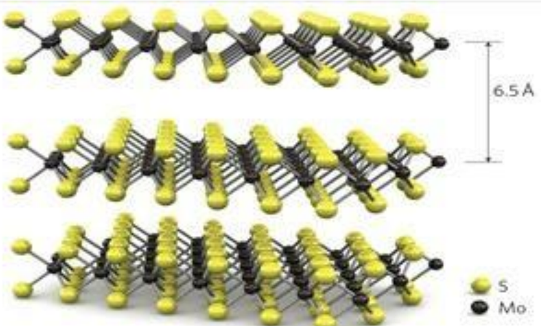
Introduction

Layered Materials I

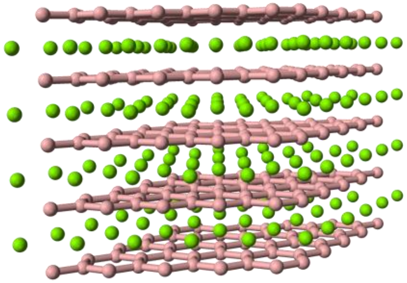

C (graphite)

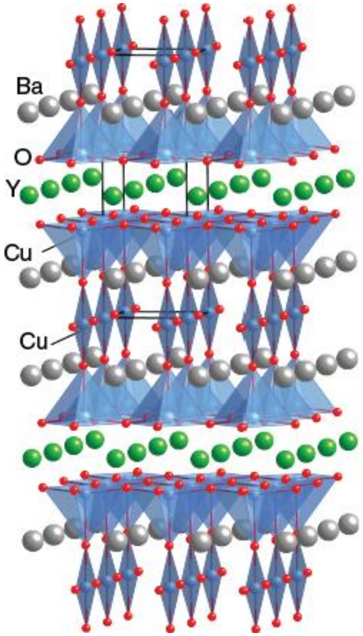

BN (white graphite)


P (black-P)

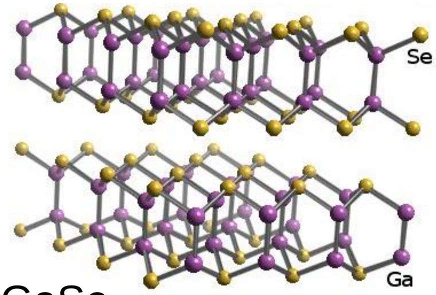


MoS_2 (transition metal dichalcogenide)


MgB_2

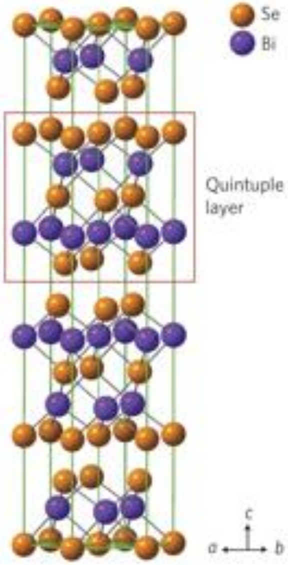


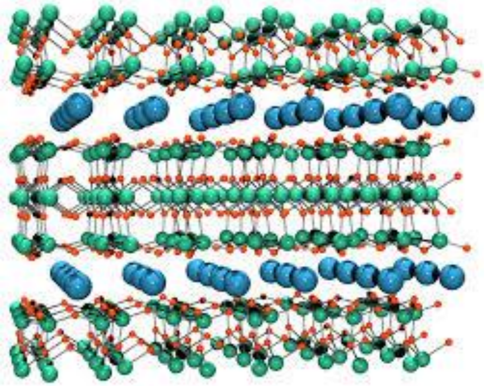
$YBa_2Cu_3O_{7-x}$ (high-T_c cuprate)

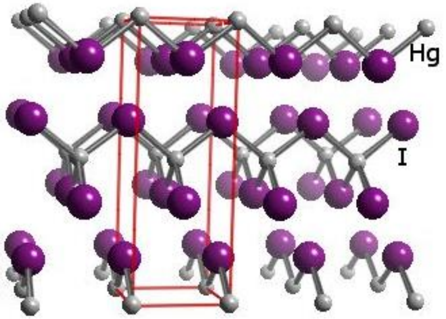


GaSe (group III monochalcogenide)

Bi_2Se_3 (sesquichalcogenide)




(mica)



HgI_2 (transition metal halide)

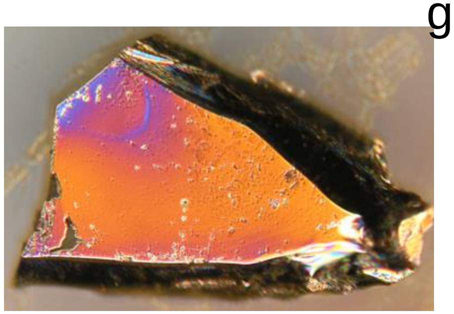
Layered Materials II

C (graphite)

BN (white graphite)

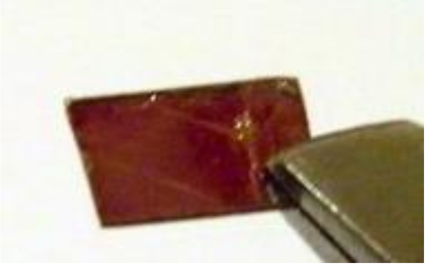
P (black-P)

MoS$_2$ (transition metal dichalcogenide)



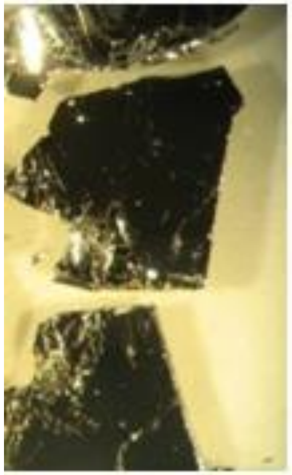
MgB$_2$

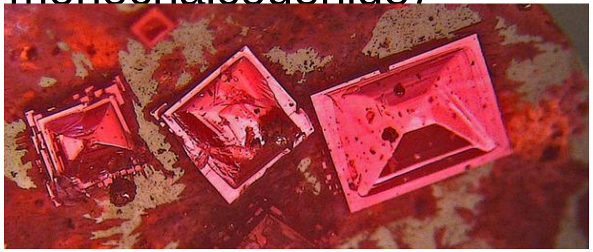
YBa$_2$Cu$_3$O$_{7-x}$ (high-T$_c$ cuprate)



GaSe (group III monochalcogenide)

Bi$_2$Se$_3$ (sesquichalcogenide)





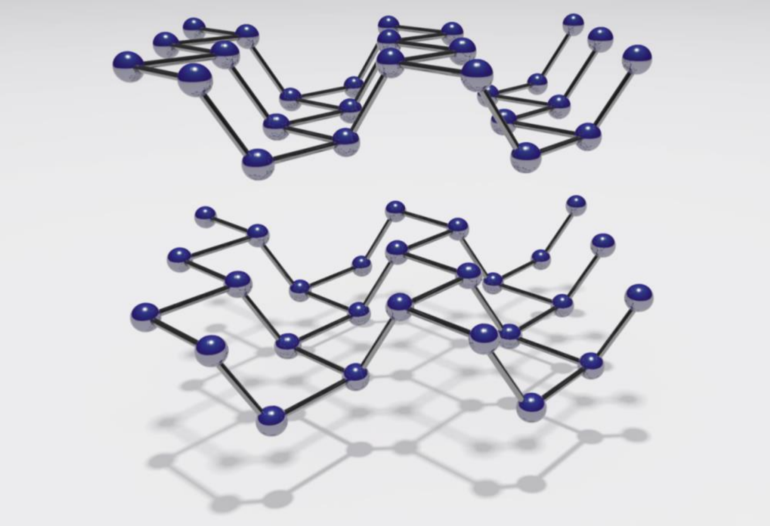
HgI$_2$ (transition metal halide)

(mica)

Black Phosphorus

Only the second elemental allotrope that can be mechanically exfoliated down to the single atomic layer limit.

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 Peide Ye (Purdue), Yuanbo Zhang (Fudan) and Jeanie Lau (UC Riverside)

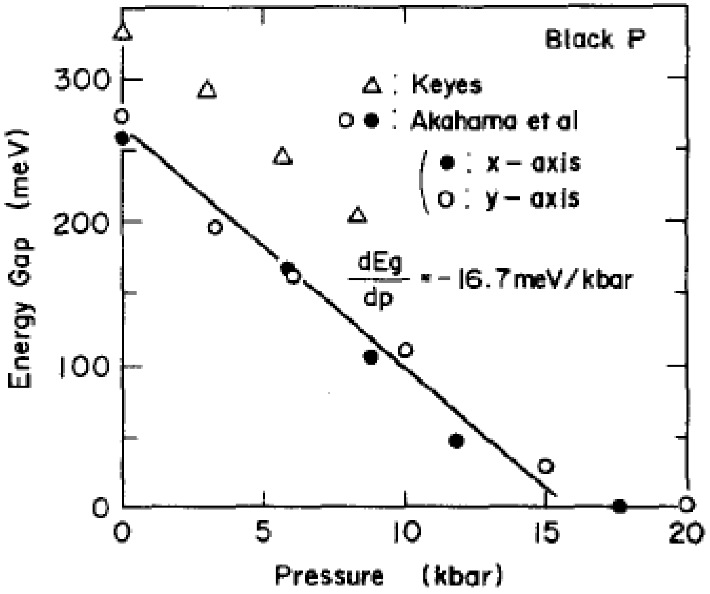
Puckered honeycomb layers

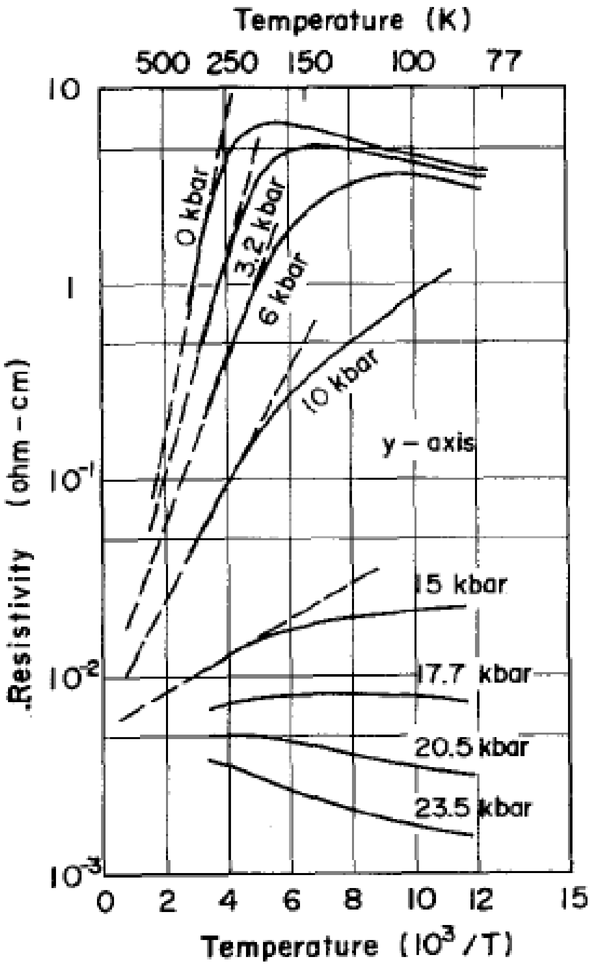
Bulk band gap = 0.3 eV

Monolayer band gap ~ 1.2 eV

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

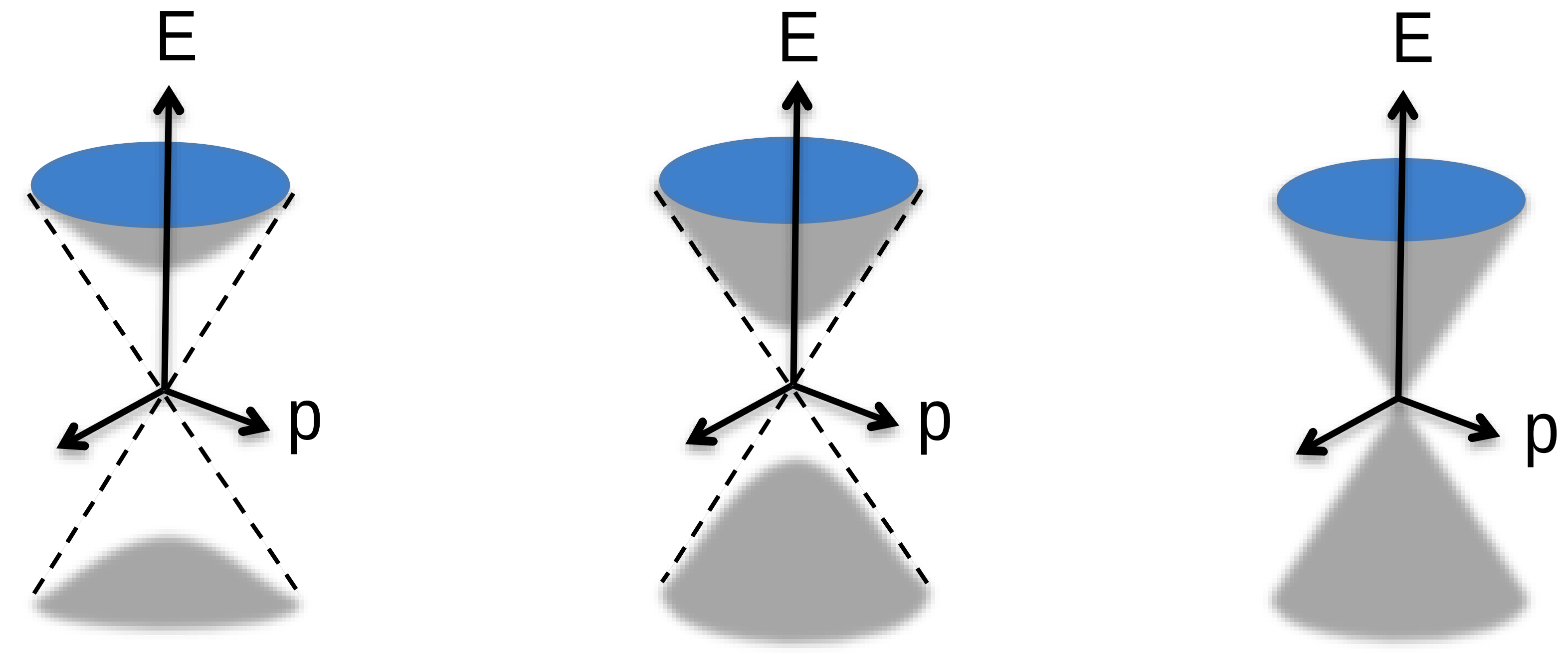
Black Phosphorus (bP)





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

Black Phosphorus (bP)



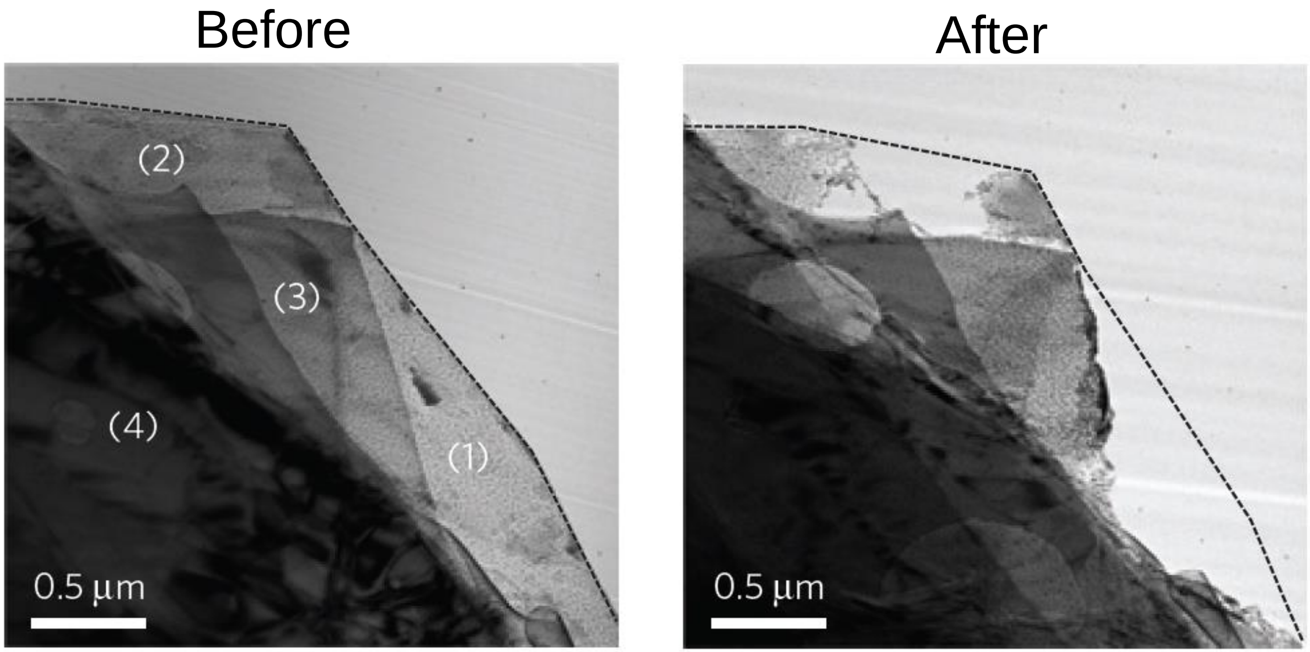
Schrödinger

strain, electric field

Dirac

Xiang et al., Phys. Rev. Lett. 115, 186402 (2015)

bP Photo-oxidation: 20s of Ambient Air and Light

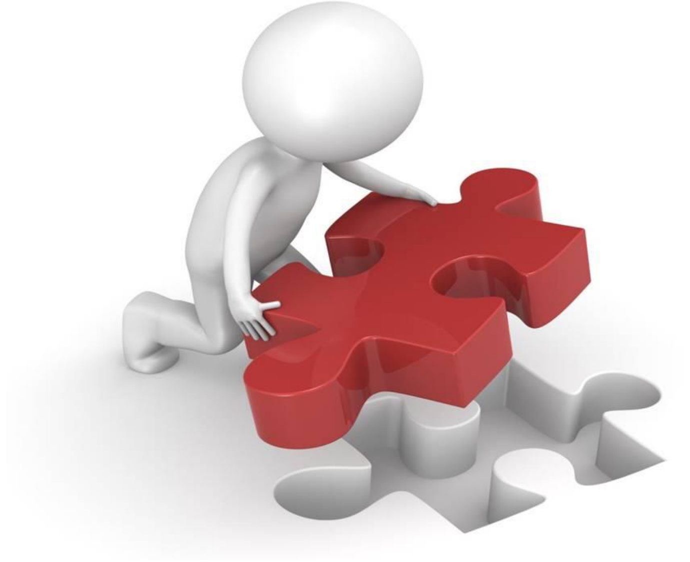

Before

After

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

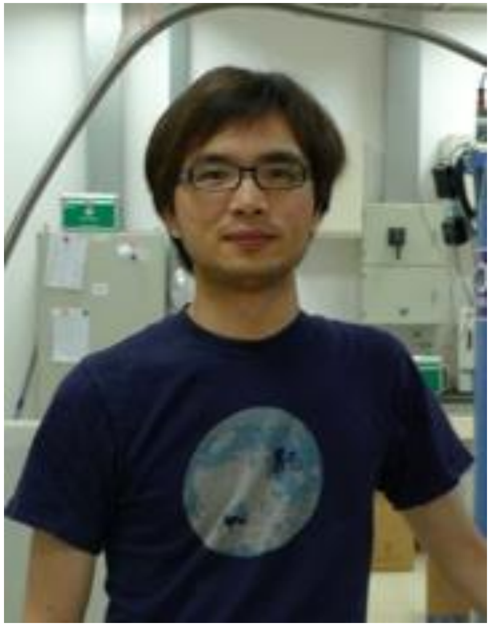
A. Favron … R. Martel, “*Photo-oxidation and quantum confinement effects in exfoliated black phosphorus*”, Nature Materials (2015).

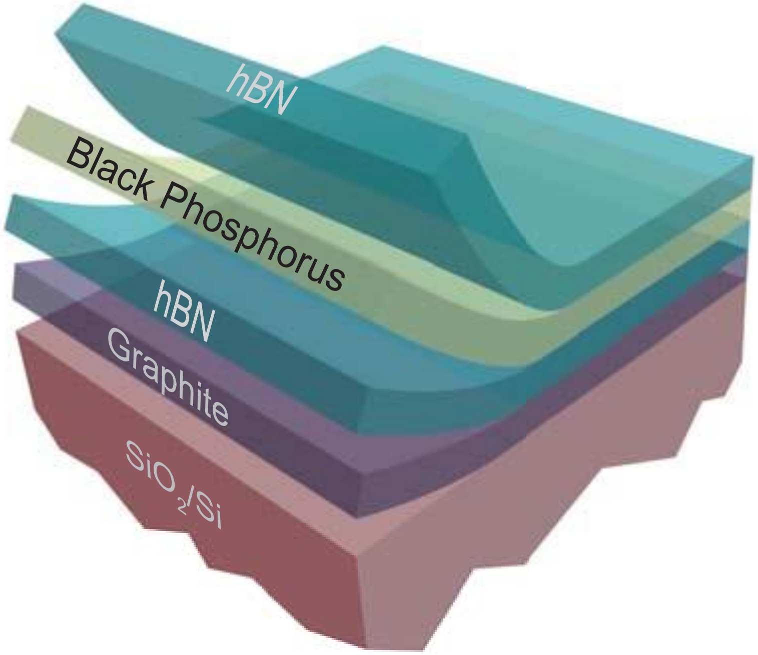
Device Fabrication and Measurements



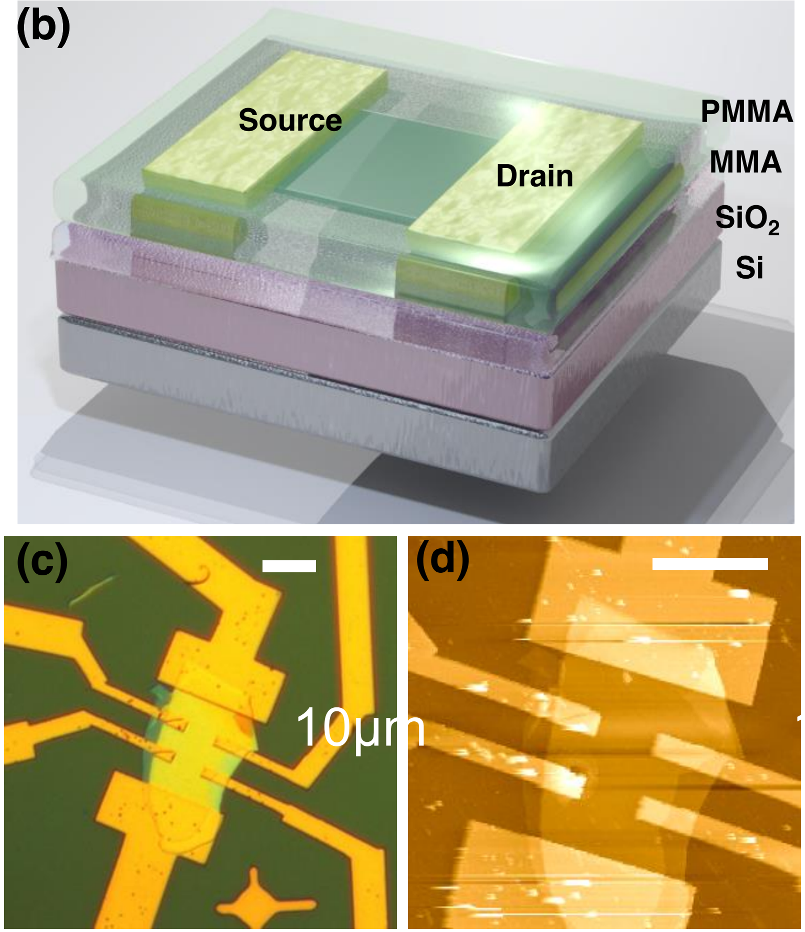
bP FET Fabrication : Top Approach

Prof. Yuanbo Zhang, Fudan





bP FET Fabrication : a Poor Man’s Approach



bulk bP source:

99.98% purity (Smart Elements)

exfoliation & processing in glove box

O_2, H_2O < 1ppm

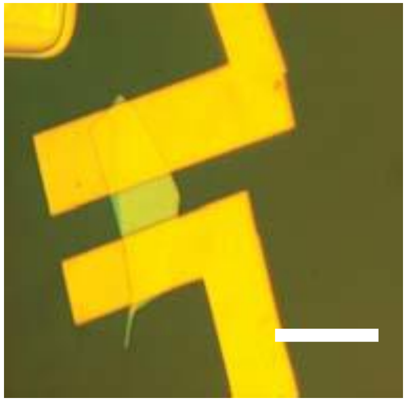
e-beam lithography & Ti/Au contacts

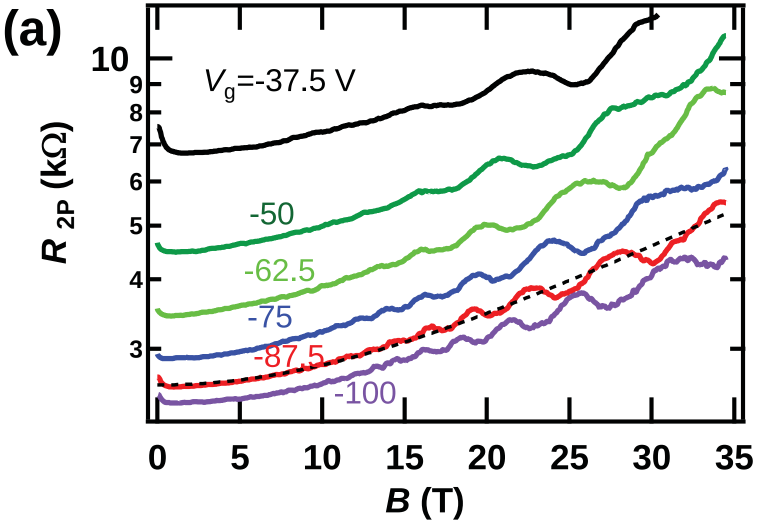
encapsulation with MMA/PMMA

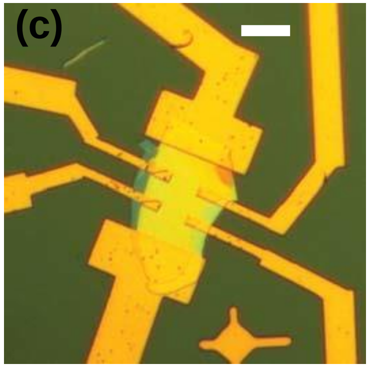
avoid simultaneous O_2, H_2O, and light

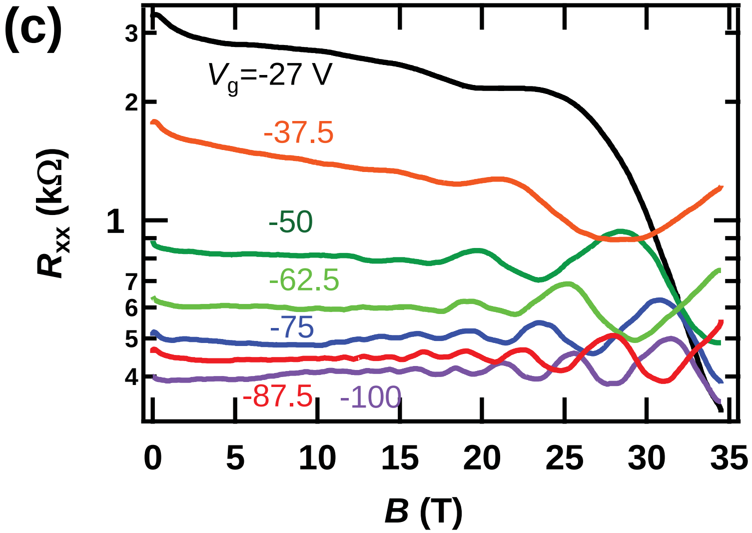
Our best mobility: ~1000 $cm^2/V.s$

Shubnikov – de Haas Oscillations



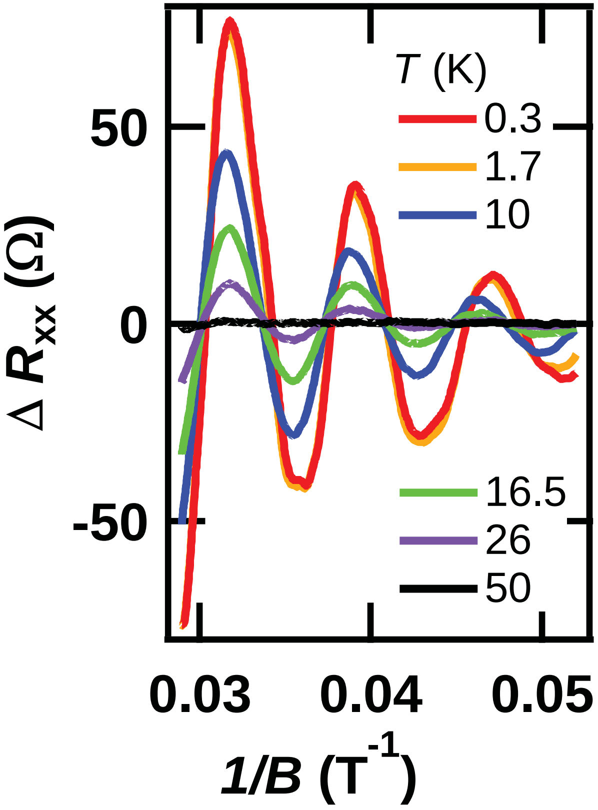


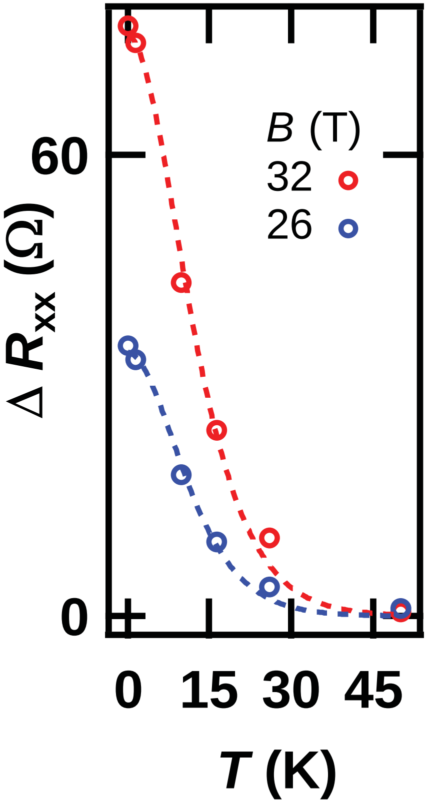




V. Tayari, ………G. Gervais, R. Martel, T. Szkopek Nature Communications (2015

Temperature Dependence of SdH





Lifshitz-Kosevich:

$$\Delta R = R(B,T)\cos\left(2\pi\frac{B_F}{B}+\phi\right)$$

Damping:

$$R(B,T) = R_0\exp(-\Lambda_D)\frac{\Lambda_T}{\sinh\Lambda_T}$$

$$\Lambda_T = \frac{2\pi^2 m^* k_B T}{\hbar e B}$$

$$\Lambda_D = \frac{2\pi^2 m^* k_B T_D}{\hbar e B}$$

$m^*=0.36$ +/- $0.03\ m_0$

V. Tayari, ………G. Gervais, R. Martel, T. Szkopek Nature Communications (2015

McGill

Gervais Lab

Independent Findings

Independent work regarding SdH

Jeanie Lau @ UC Riverside:
N. Gillgren et al., *Gate tuneable quantum oscillations in air-stable and high-mobility few-layer phosphorene heterostructures*, 2D Materials 2015.

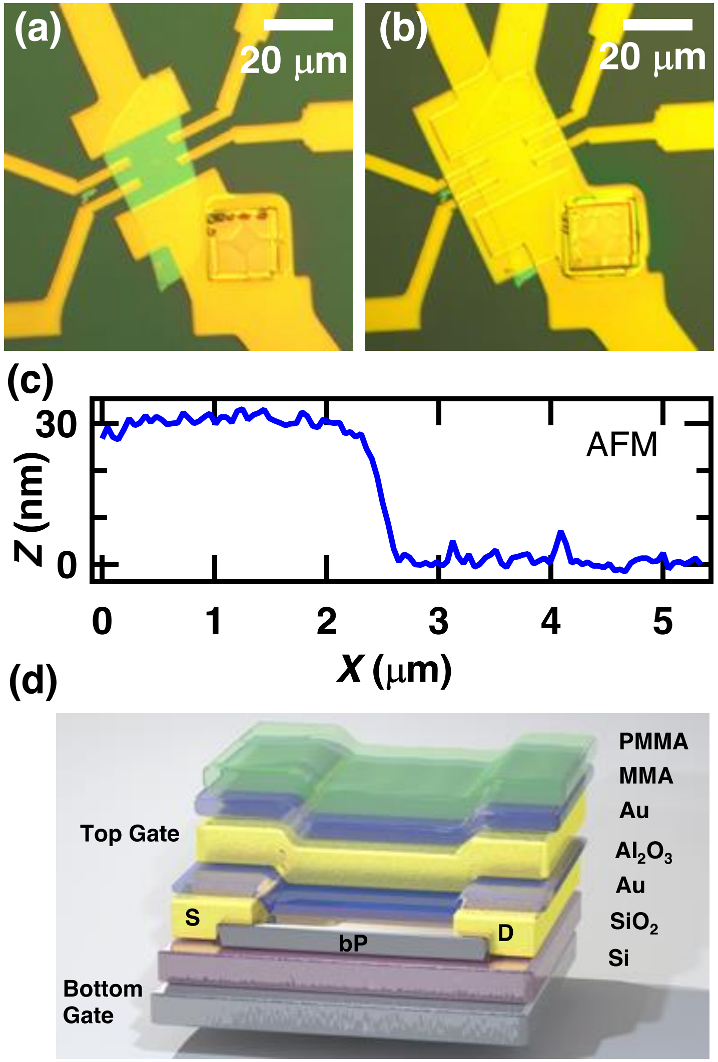
Yuanbo Zhang @ Fudan:
L. Li et al., *Quantum oscillations in black phosphorus two-dimensional electron gas*, Nature Nanotechnology 2015.

Ning Wang @ HKUST:
X. Chen et al., *High quality sandwiched black phosphorus heterostructure and its quantum oscillations*, Nature Communications 2015.

Gervais/Szkopek @ McGill + Martel @ UdeM team:
V. Tayari et al., *Two dimensional magnetotransport in a naked black phosphorus quantum well*, Nature Communications 2015.

New Developments in Bp: Device Engineering

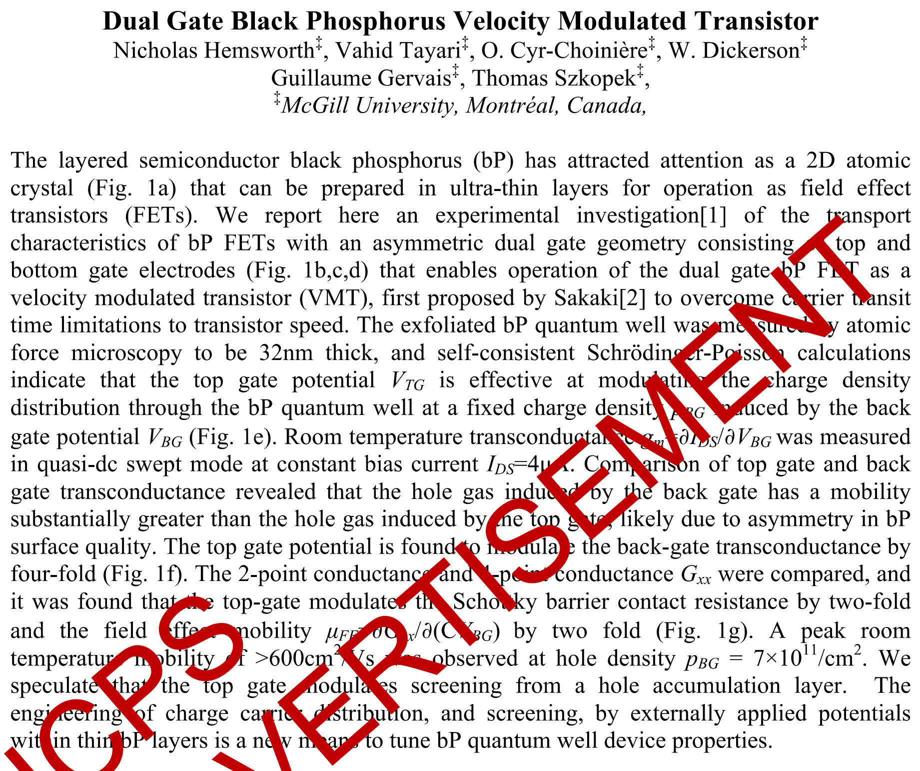
Dual Gated Velocity Modulator (Engineering)



V. Tayari, ………G. Gervais, T. Szkopek Phys. Rev. Applied 5, 064004 (2015

See Talk by Prof. Szkopek @ ICPS

Monday 14h: 2D Materials beyond graphene (Mo-E3)



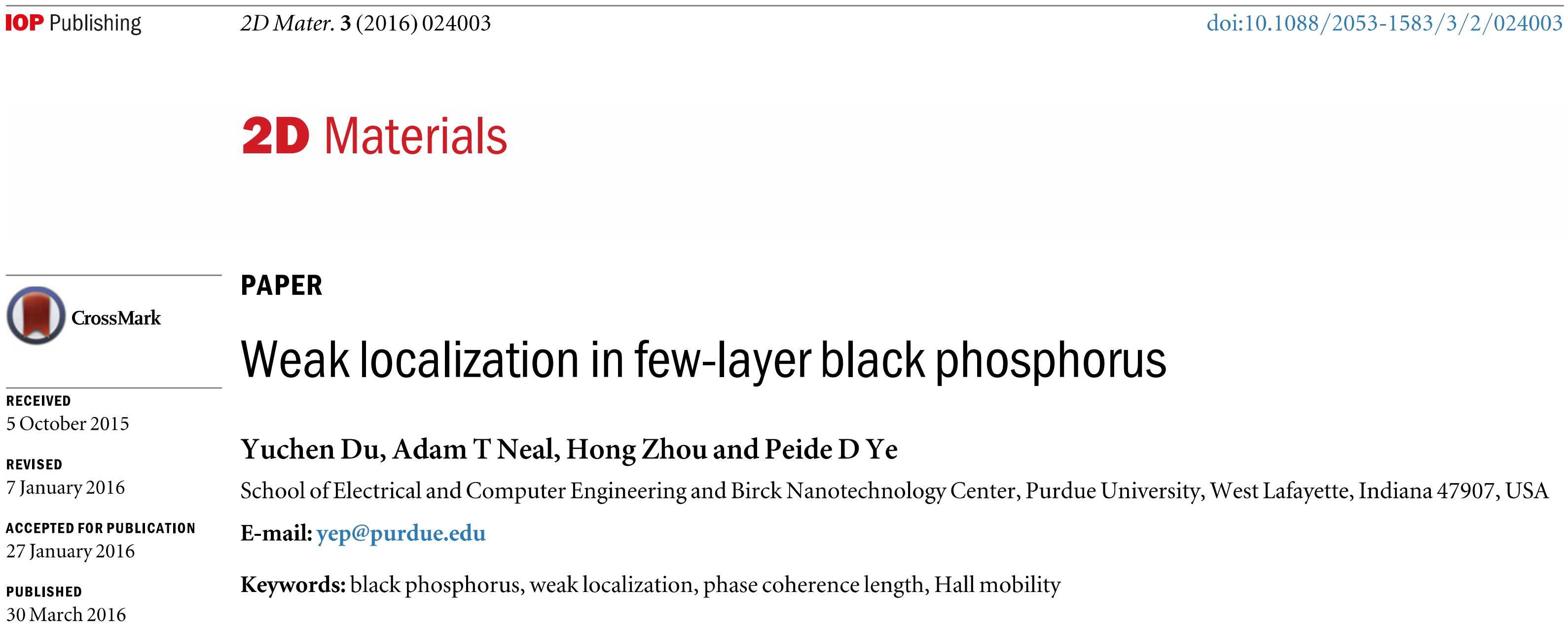
Dual Gate Black Phosphorus Velocity Modulated Transistor

Nicholas Hemsworth[‡], Vahid Tayari[‡], O. Cyr-Choinière[‡], W. Dickerson[‡]
Guillaume Gervais[‡], Thomas Szkopek[‡],
[‡]*McGill University, Montréal, Canada,*

The layered semiconductor black phosphorus (bP) has attracted attention as a 2D atomic crystal (Fig. 1a) that can be prepared in ultra-thin layers for operation as field effect transistors (FETs). We report here an experimental investigation[1] of the transport characteristics of bP FETs with an asymmetric dual gate geometry consisting of top and bottom gate electrodes (Fig. 1b,c,d) that enables operation of the dual gate bP FET as a velocity modulated transistor (VMT), first proposed by Sakaki[2] to overcome carrier transit time limitations to transistor speed. The exfoliated bP quantum well was measured by atomic force microscopy to be 32nm thick, and self-consistent Schrödinger-Poisson calculations indicate that the top gate potential V_{TG} is effective at modulating the charge density distribution through the bP quantum well at a fixed charge density p_{BG} induced by the back gate potential V_{BG} (Fig. 1e). Room temperature transconductance $g_m=\partial I_{DS}/\partial V_{BG}$ was measured in quasi-dc swept mode at constant bias current I_{DS}=4μA. Comparison of top gate and back gate transconductance revealed that the hole gas induced by the back gate has a mobility substantially greater than the hole gas induced by the top gate, likely due to asymmetry in bP surface quality. The top gate potential is found to modulate the back-gate transconductance by four-fold (Fig. 1f). The 2-point conductance and 4-point conductance G_{xx} were compared, and it was found that the top-gate modulates the Schottky barrier contact resistance by two-fold and the field effect mobility $\mu_{FE}=\partial G_{xx}/\partial(CV_{BG})$ by two fold (Fig. 1g). A peak room temperature mobility of >600cm^2/Vs was observed at hole density p_{BG} = 7×10^{11}/cm^2. We speculate that the top gate modulates screening from a hole accumulation layer. The engineering of charge carrier distribution, and screening, by externally applied potentials within thin bP layers is a new means to tune bP quantum well device properties.

New Developments in Bp: Dephasing

Recent Work on Weak Localization in bP (Purdue)



IOP Publishing 2D Mater. **3** (2016) 024003 doi:10.1088/2053-1583/3/2/024003

2D Materials

PAPER

CrossMark

RECEIVED
5 October 2015

REVISED
7 January 2016

ACCEPTED FOR PUBLICATION
27 January 2016

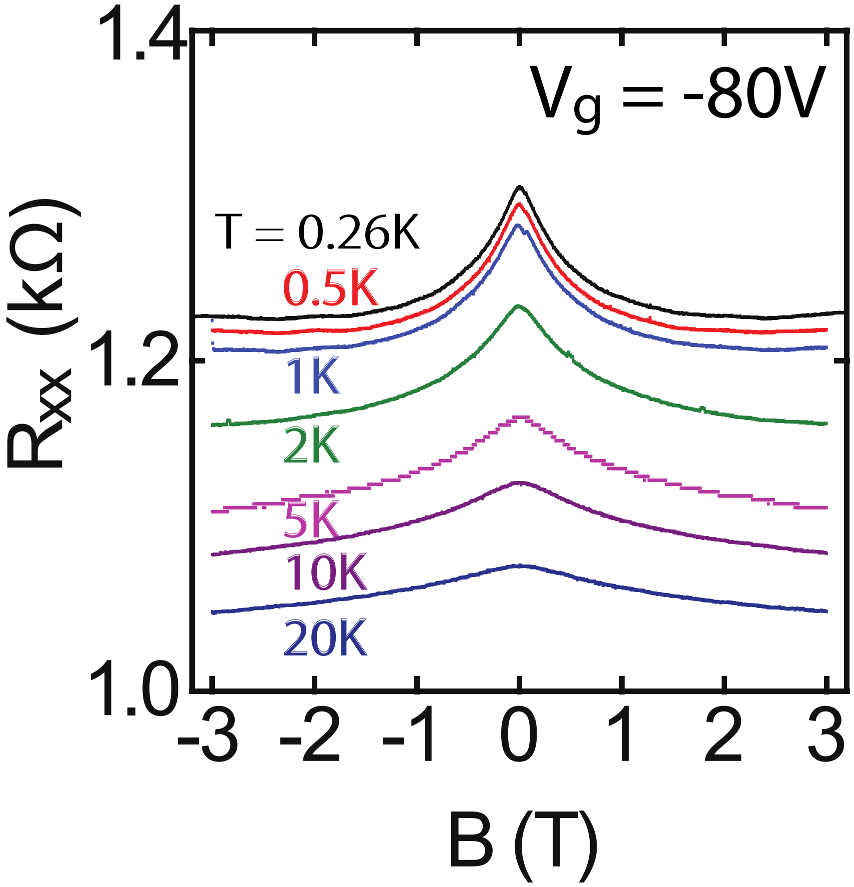
PUBLISHED
30 March 2016

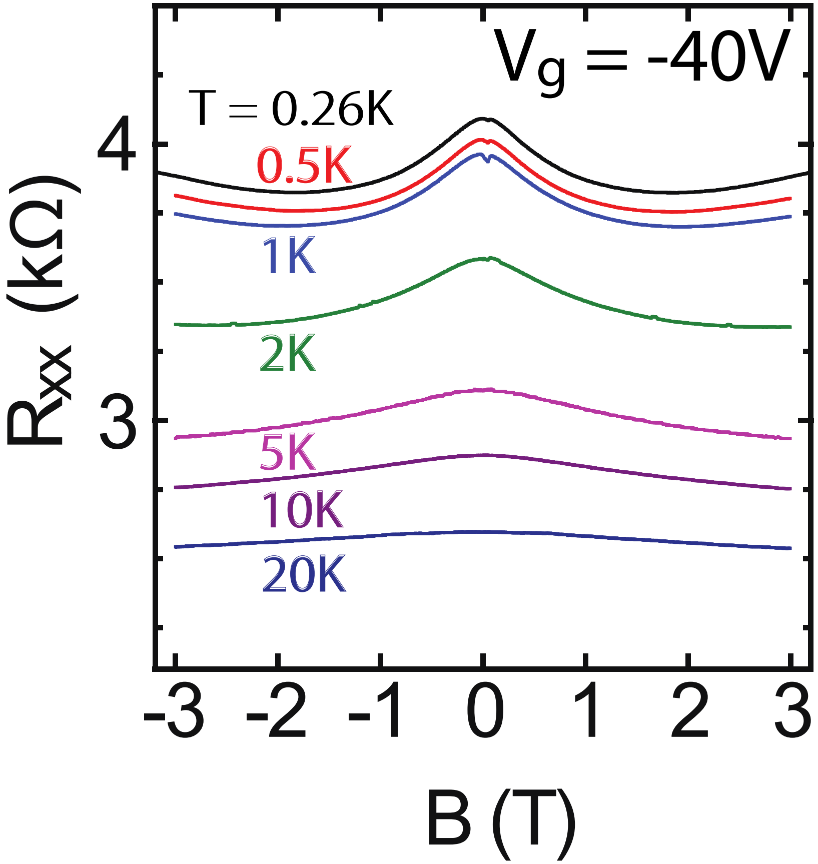
Weak localization in few-layer black phosphorus

Yuchen Du, Adam T Neal, Hong Zhou and Peide D Ye
School of Electrical and Computer Engineering and Birck Nanotechnology Center, Purdue University, West Lafayette, Indiana 47907, USA
E-mail: yep@purdue.edu

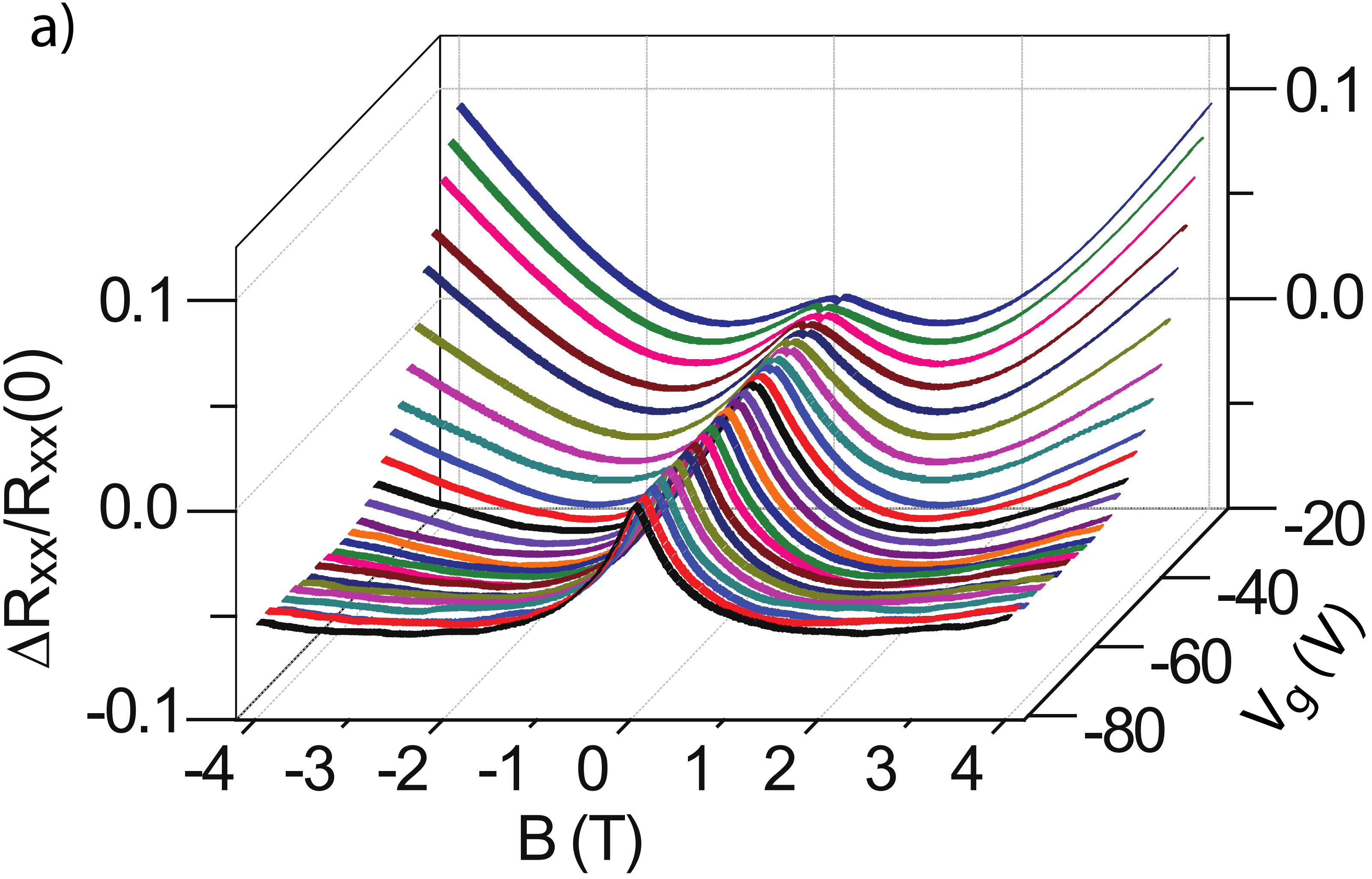
Keywords: black phosphorus, weak localization, phase coherence length, Hall mobility

Weak Localization in bP (McGill/Pisa)





Weak Localization in bP (McGill-Pisa)



Hikami-Larkin-Nagaoka (HLN) Theory

WL correction to conductivity in 2D:

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

with field parameters given by:

$$\begin{aligned} B_1 &= B_0 + \xcancel{B_{so}} + \xcancel{B_s} \\ B_2 &= \xcancel{\frac{4}{3}B_{so}} + \xcancel{\frac{2}{3}B_s} + B_\phi \\ B_3 &= \xcancel{2B_s} + B_\phi \end{aligned}$$

where B_0 describes the elastic and $B\phi$ the inelastic (dephasing) scattering.

HLN Lengthscale and Timescales

Scattering length L_i associated with a field B_i :

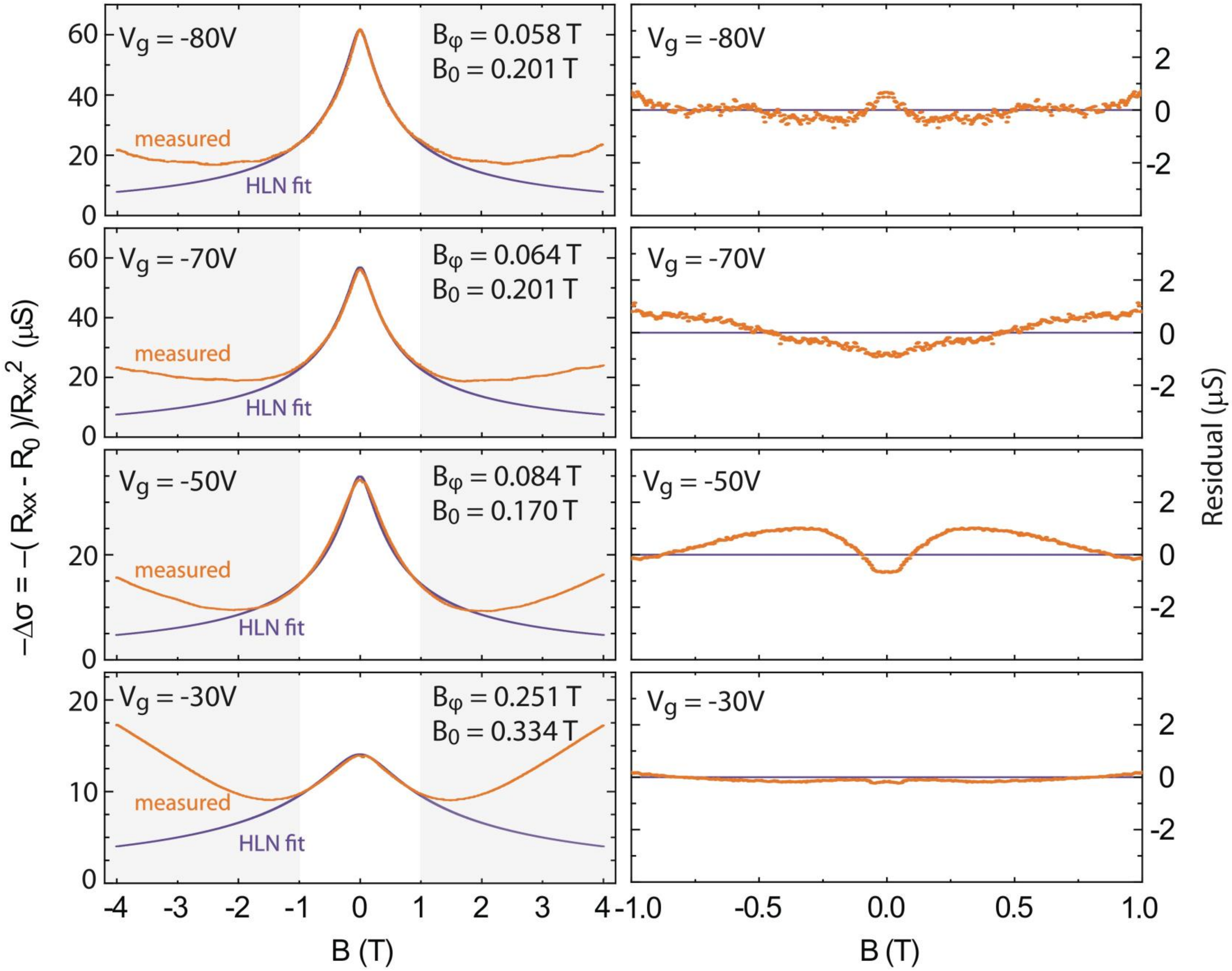
$$B_i L_i^2 = \hbar/4e$$

and correspondingly the *dephasing* time τ_n is:

$$L_\phi^2 = D\tau_\phi$$

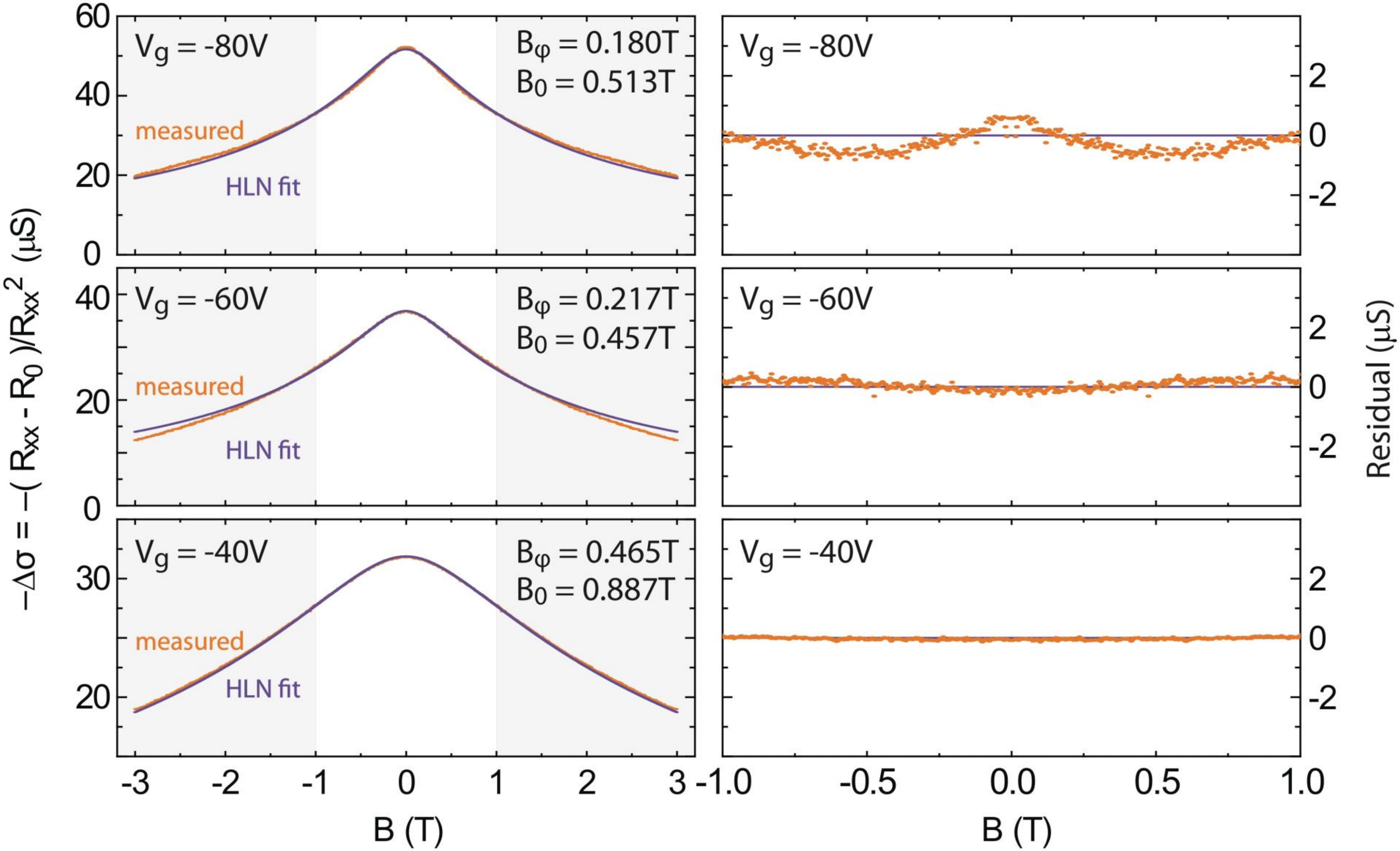
where D is the elastic coefficient diffusion.

HLN Fits (at 0.26K)



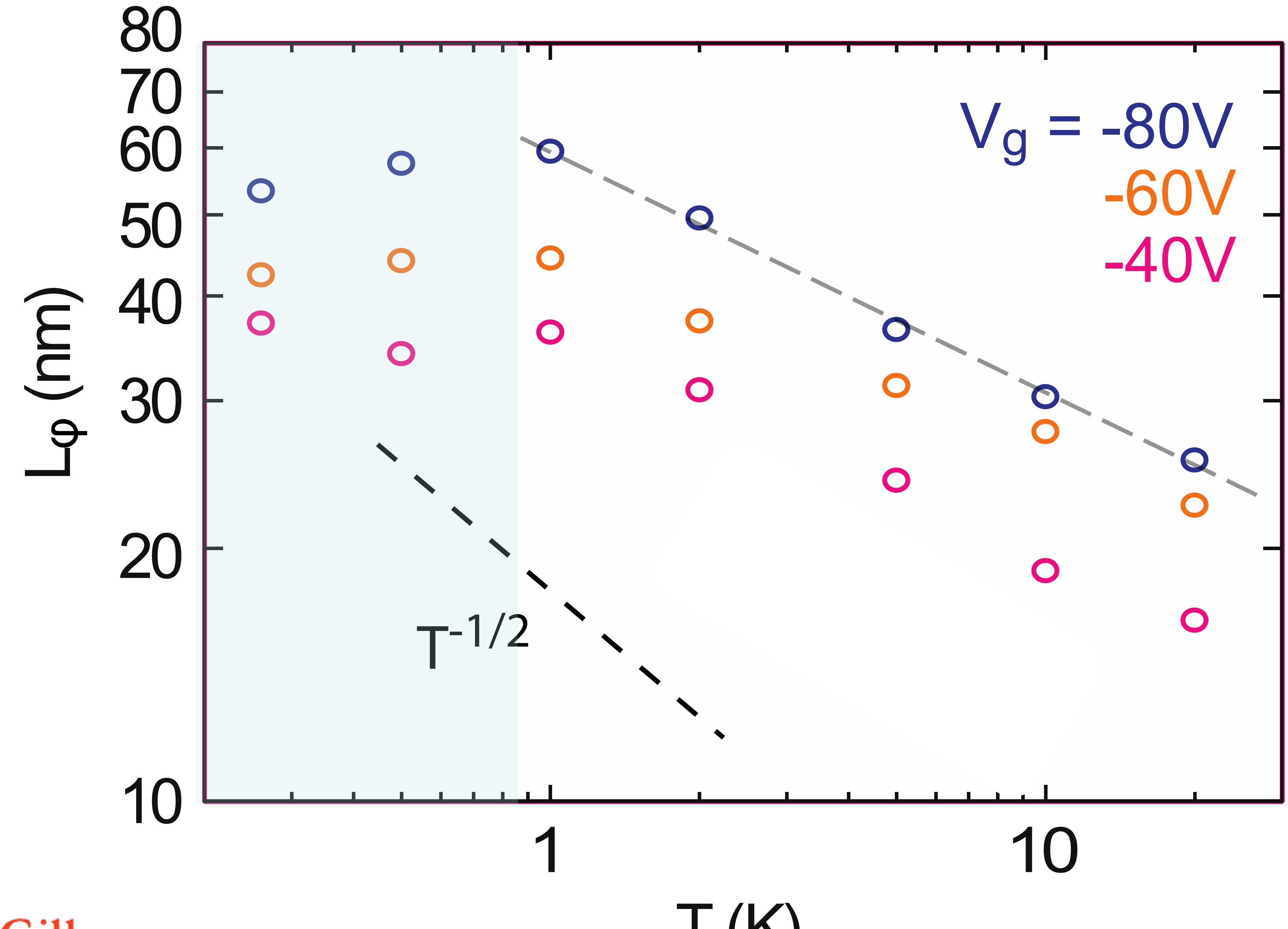
Gervais Lab

HLN Fits (at 10K)



Temperature Dependence of Dephasing Length

Lϕ

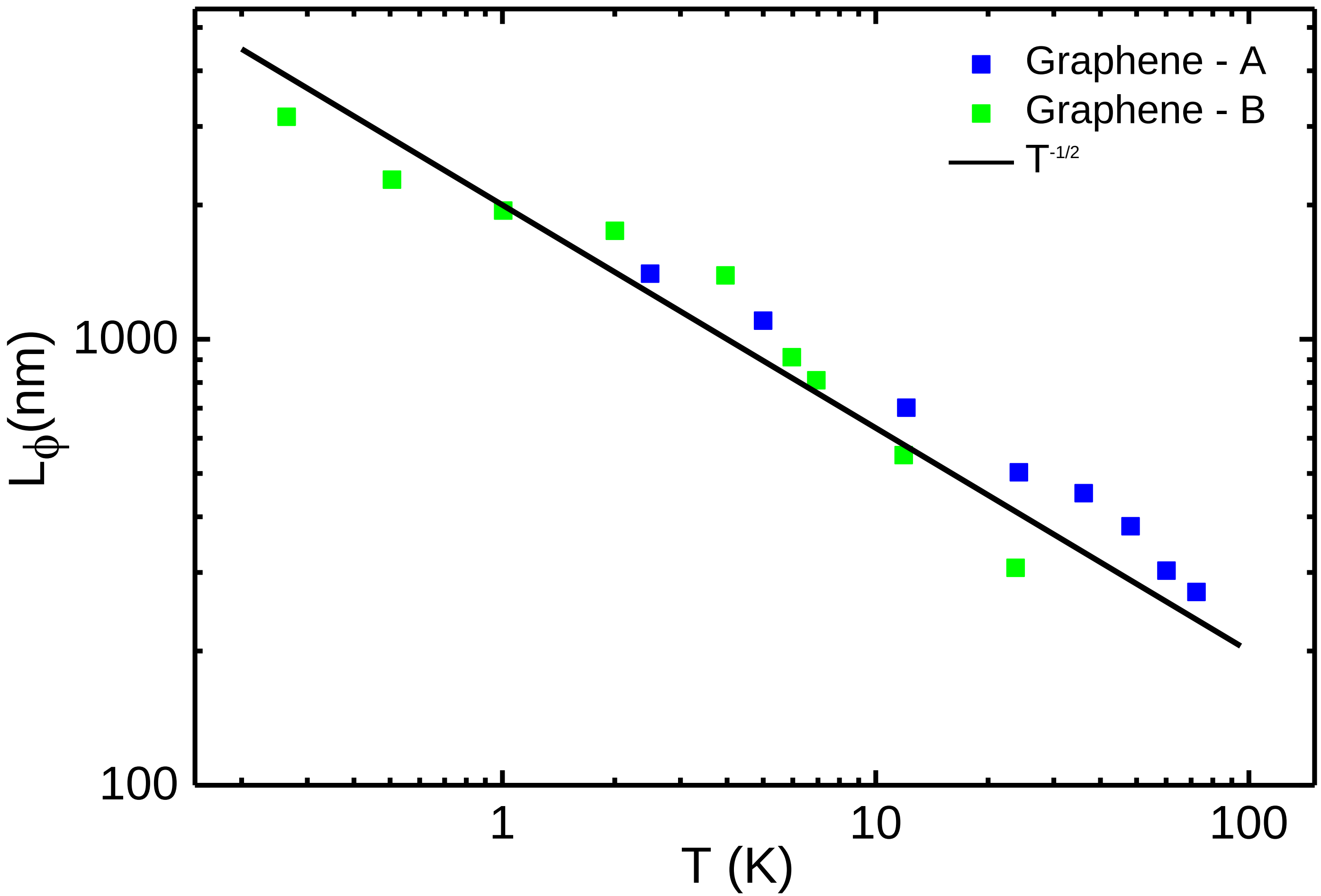


McGill

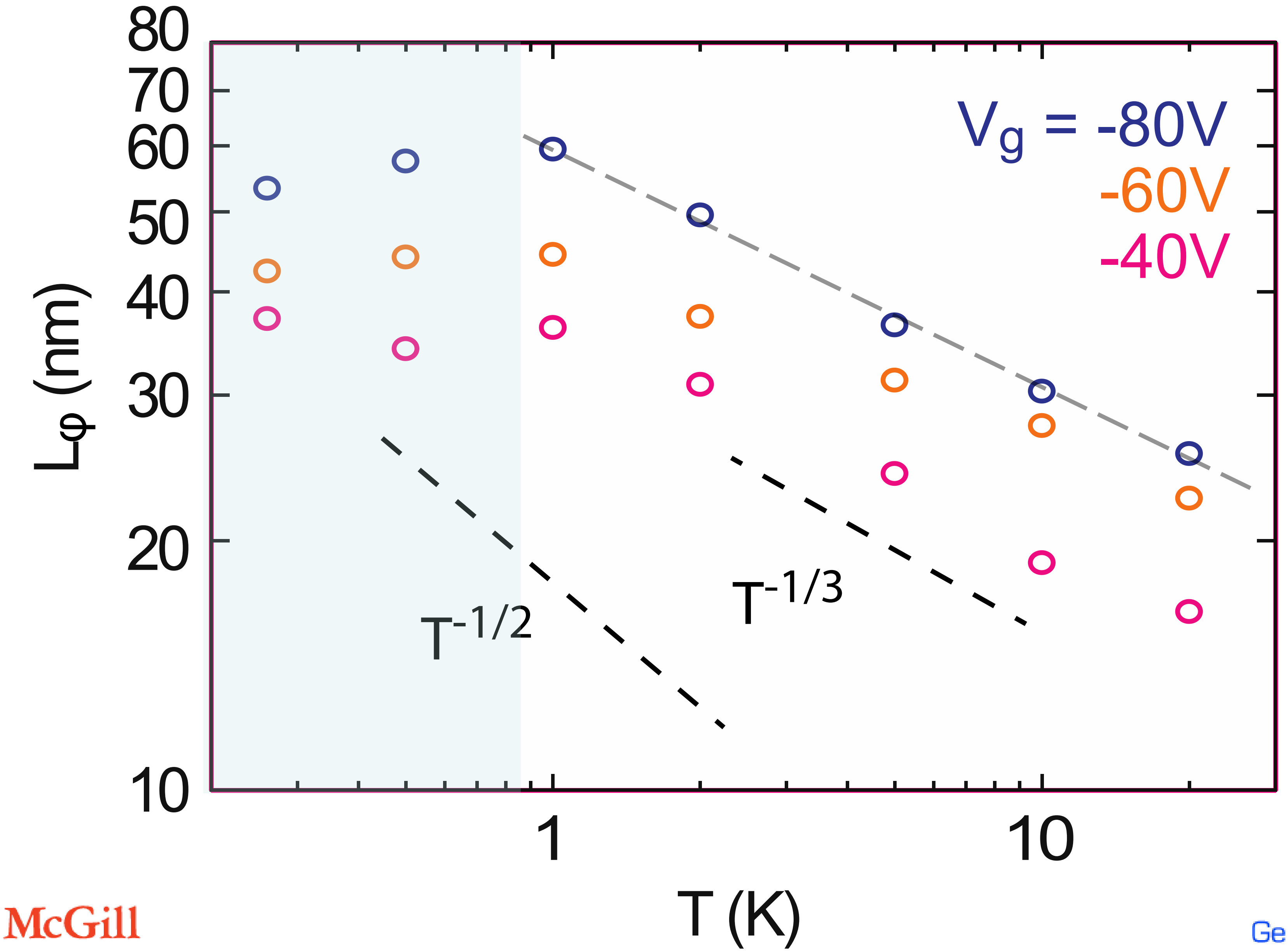
Gervais Lab

Dephasing in 2D

Electron-electron scattering in the presence of elastic scattering in

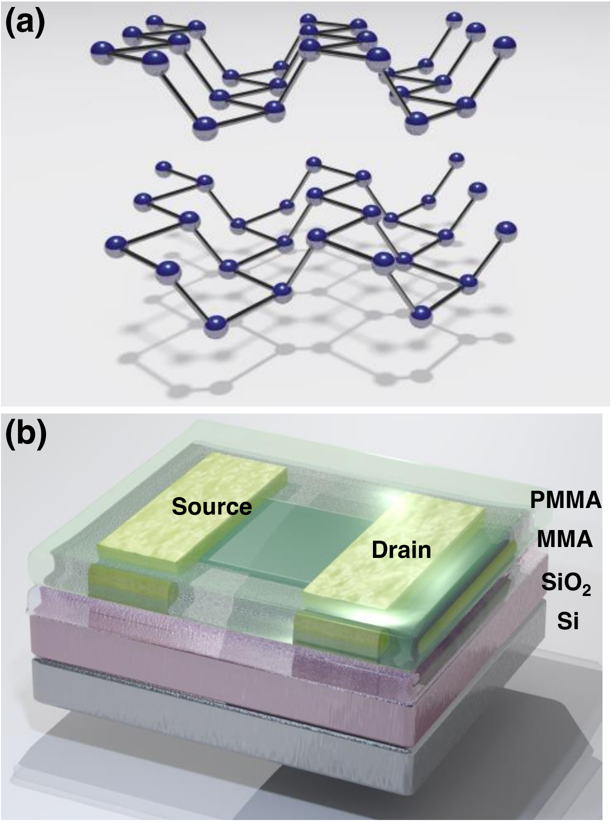


Temperature Dependence of Dephasing Length Lϕ



So, to conclude

Some Thoughts



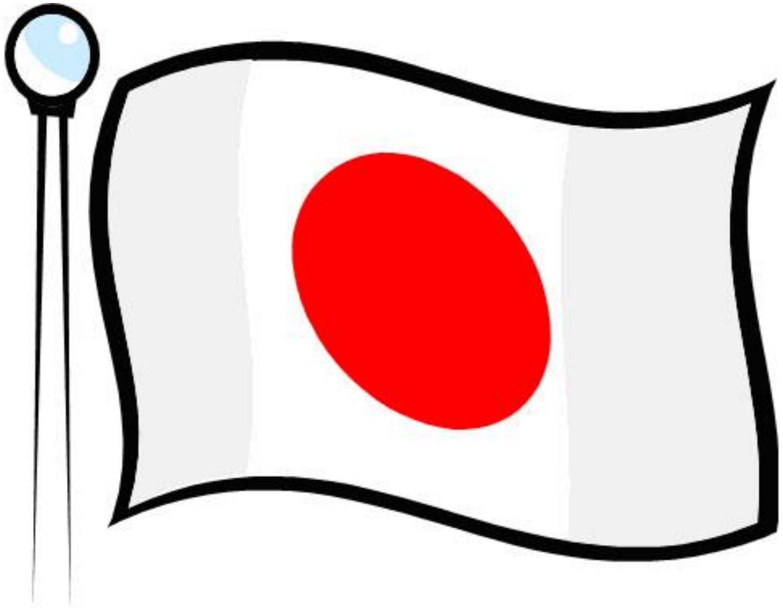
A “Puckered” Graphene experiment.

Dephasing length/time more “robust” than what is expected in 2D.

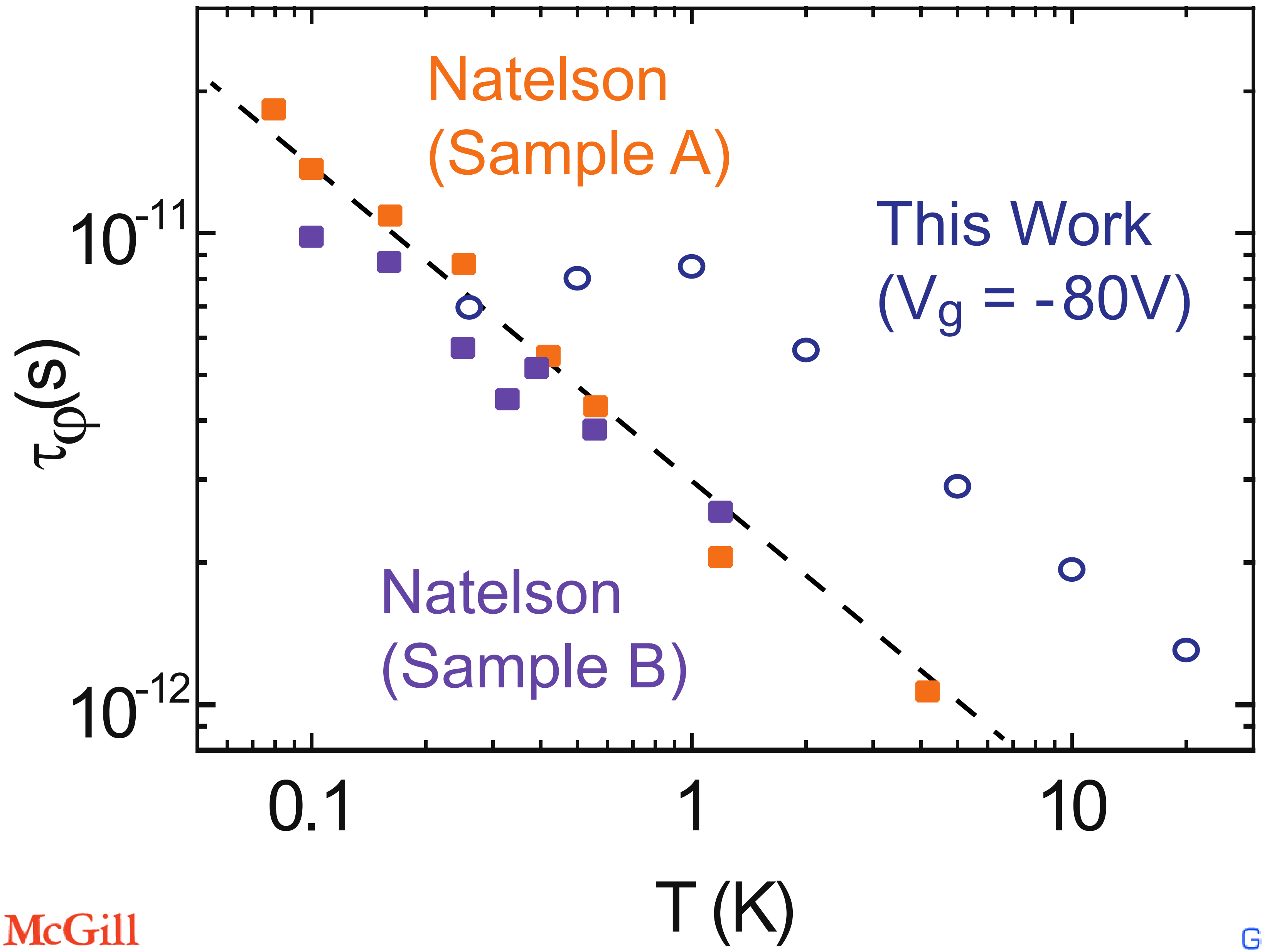
Anisotropy? “1D-like chain”?

どうもありがとうございます

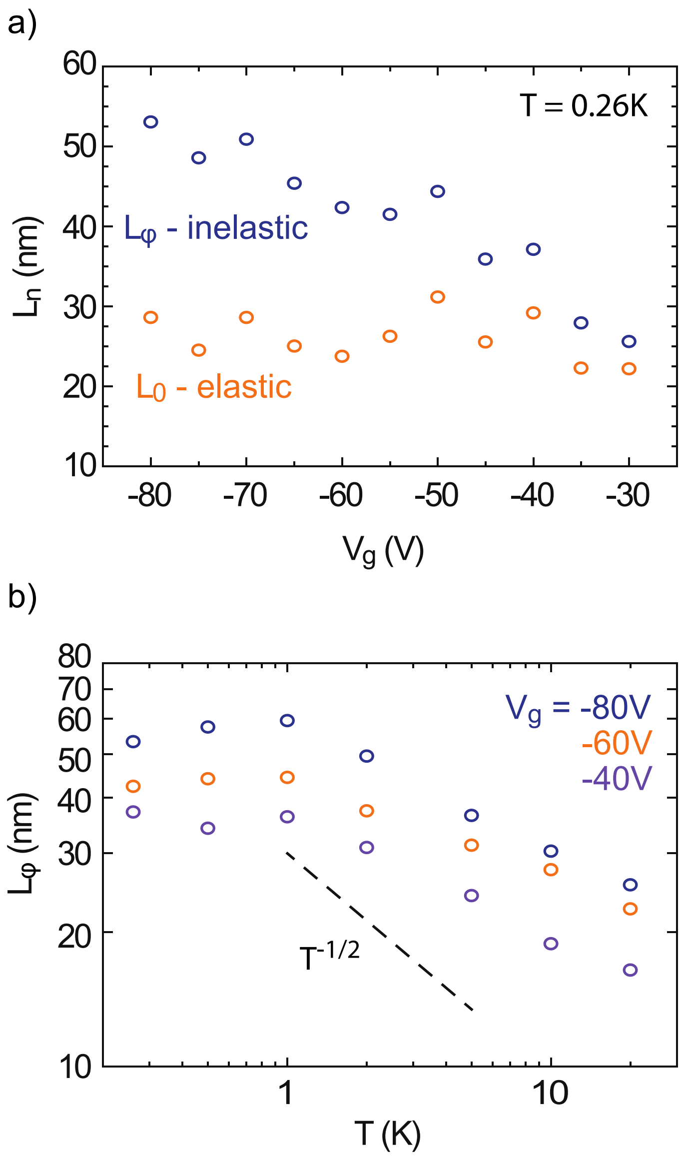
Doumo arigatou gozaimasu



Temperature Dependence of Dephasing Length



Temperature Dependence of Dephasing Length



Temperature Dependence of Dephasing Length

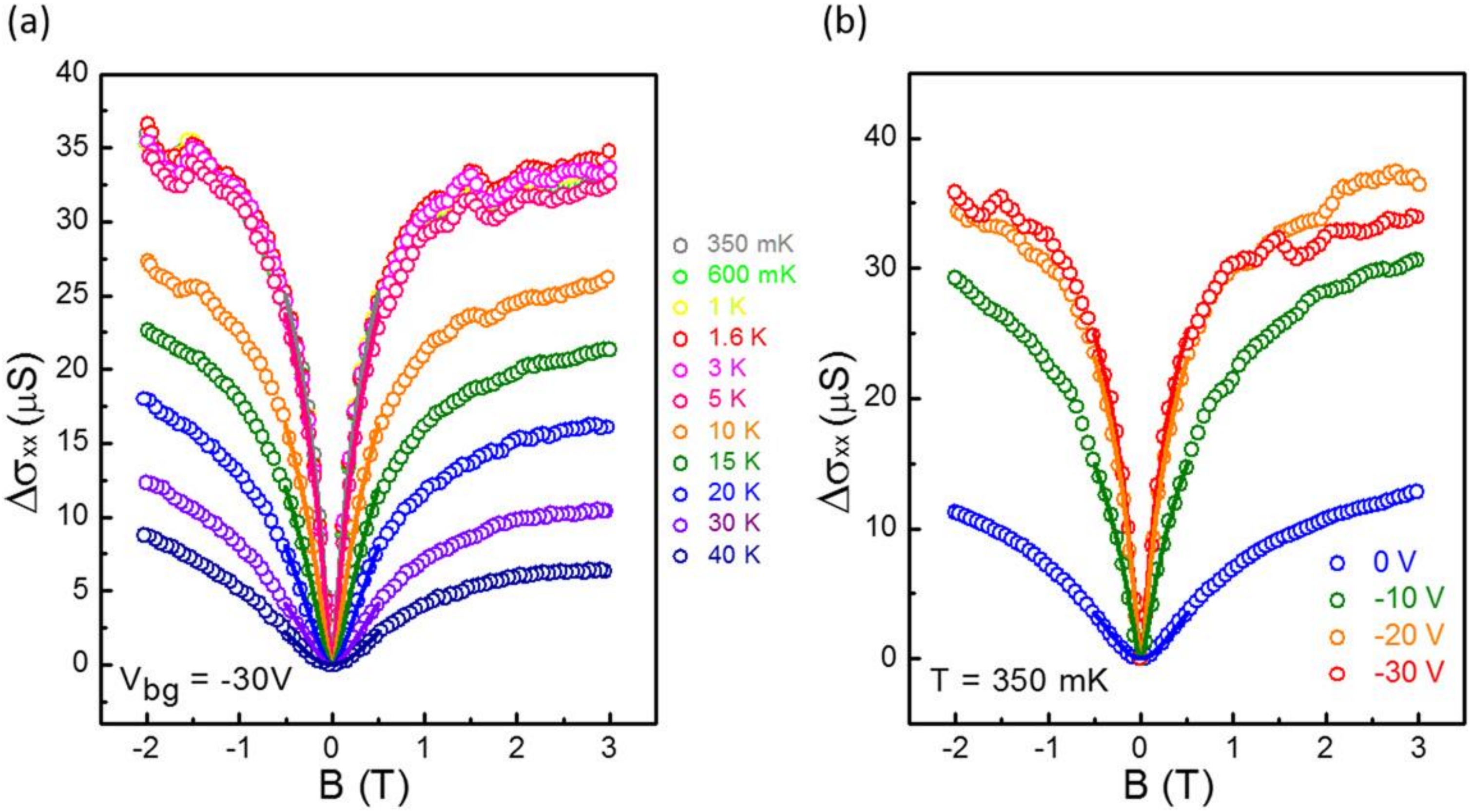
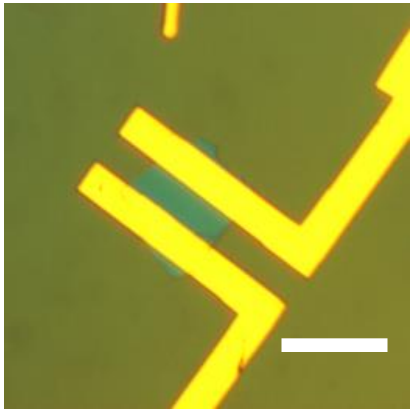


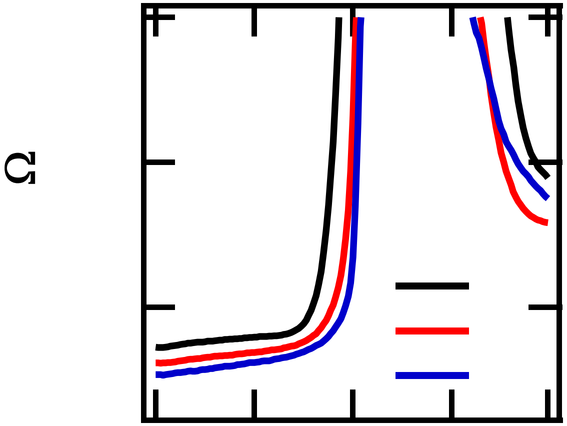
Figure 2. Magneto-conductivity measurements of weak localization (a) At constant back gate bias of −30 V for various temperatures from the base temperature of 350 mK up to 40 K. (b) At base temperature of 350 mK for back gate voltages of 0 V, −10 V, −20 V, and −30 V. The solid lines are fitting curves from HLN model within −500 mT and 500 mT.

Zero-field Transport

12.5±1 nm

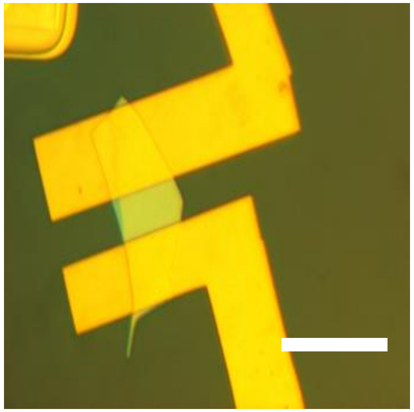
24±2 layers

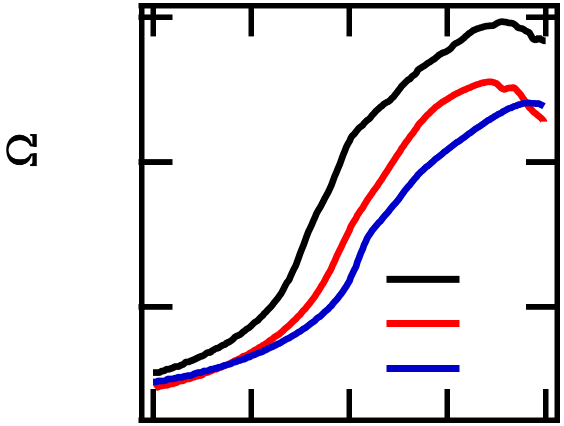




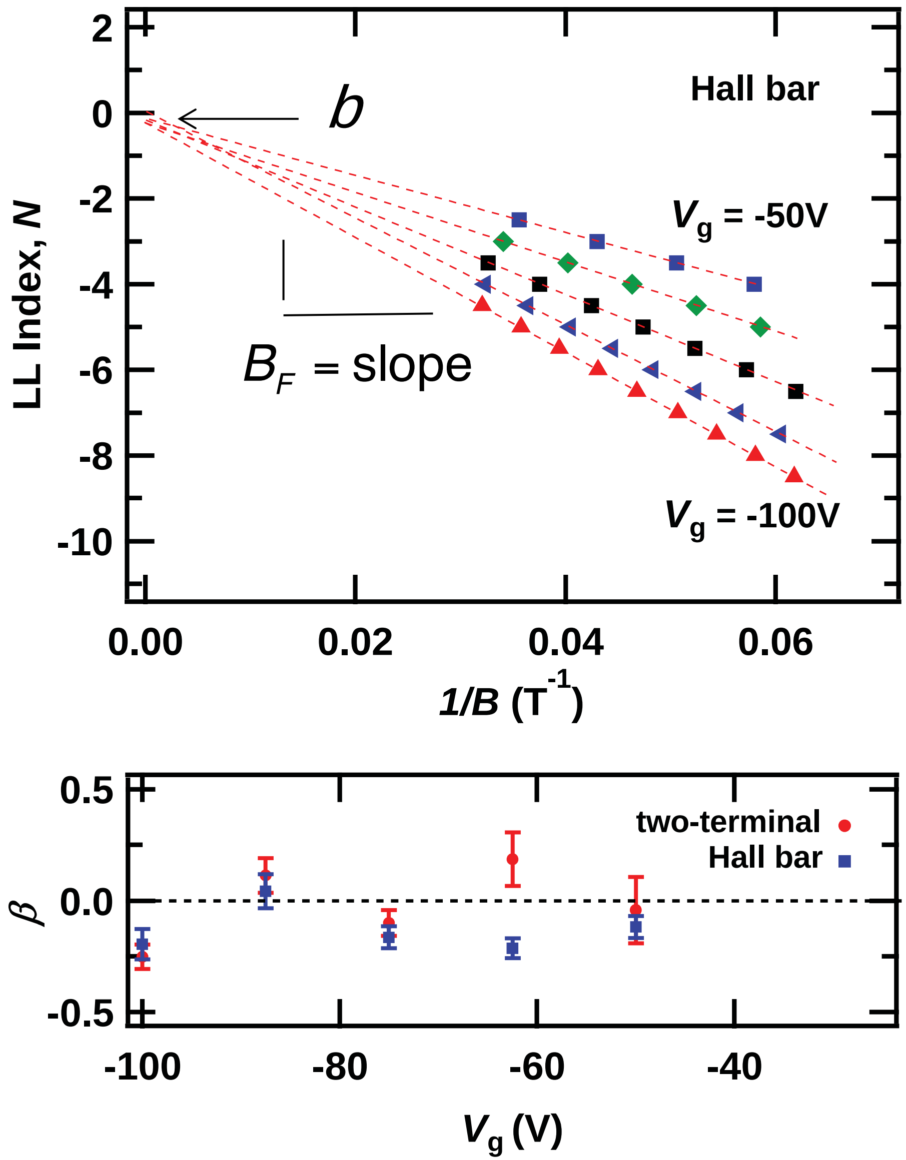
47±1 nm

90±2 layers





Landau Level Fan Diagram Analysis



Berry phase: $\Phi_B=0$

holes = Schrödinger fermions

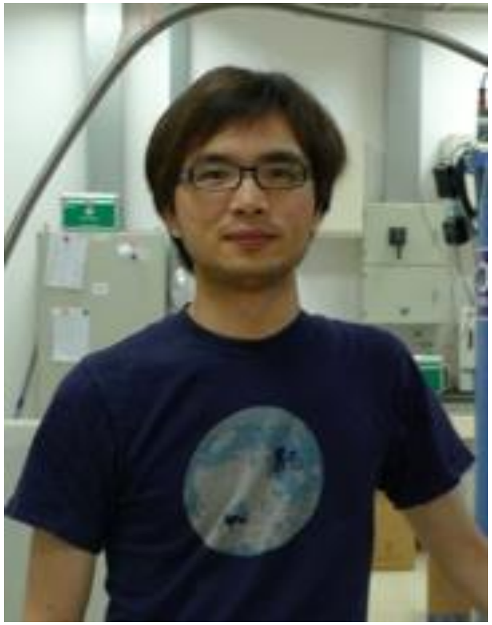
V. Tayari, ………G. Gervais, R. Martel, T. Szkopek Nature Communications (2015

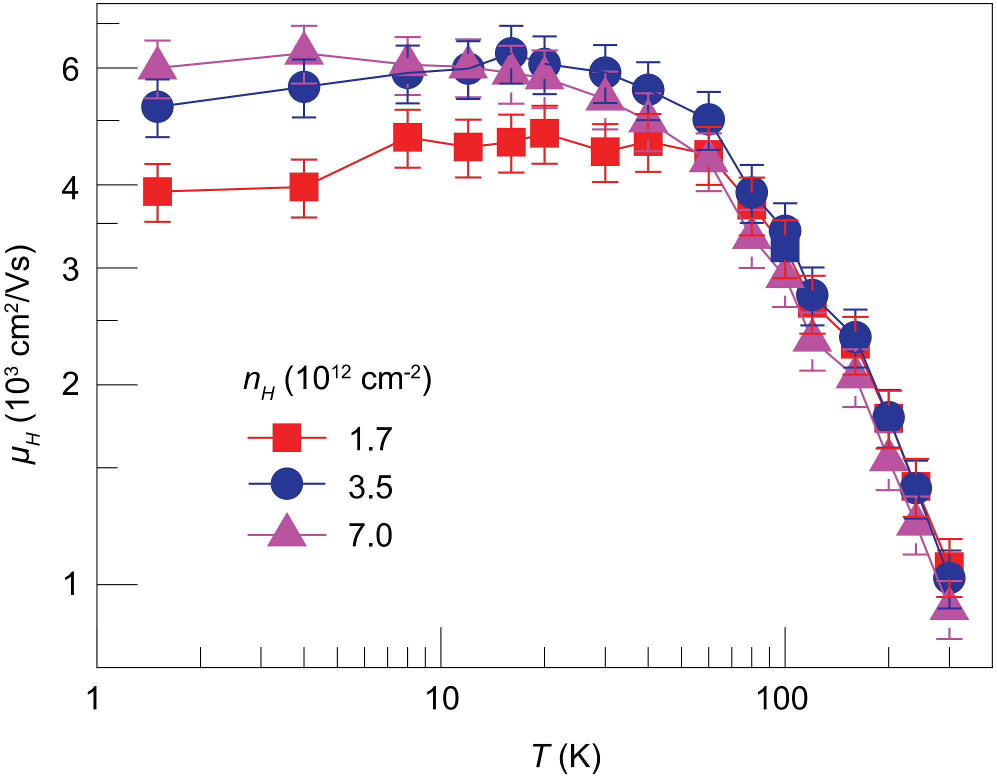
McGill

Gervais Lab

bP FET Fabrication : a Much *Better* Approach

Prof. Yuanbo Zhang

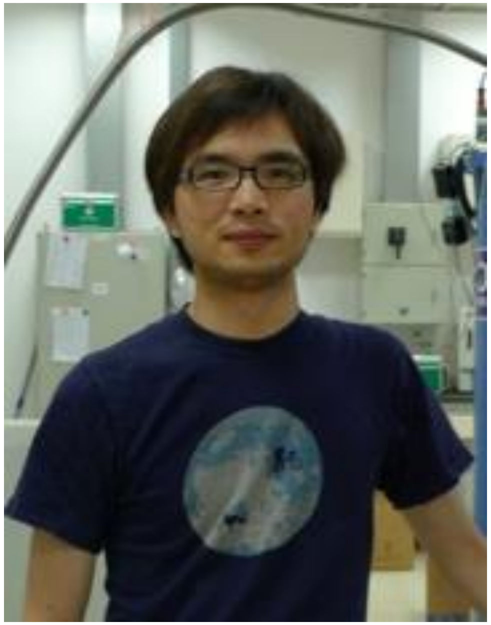


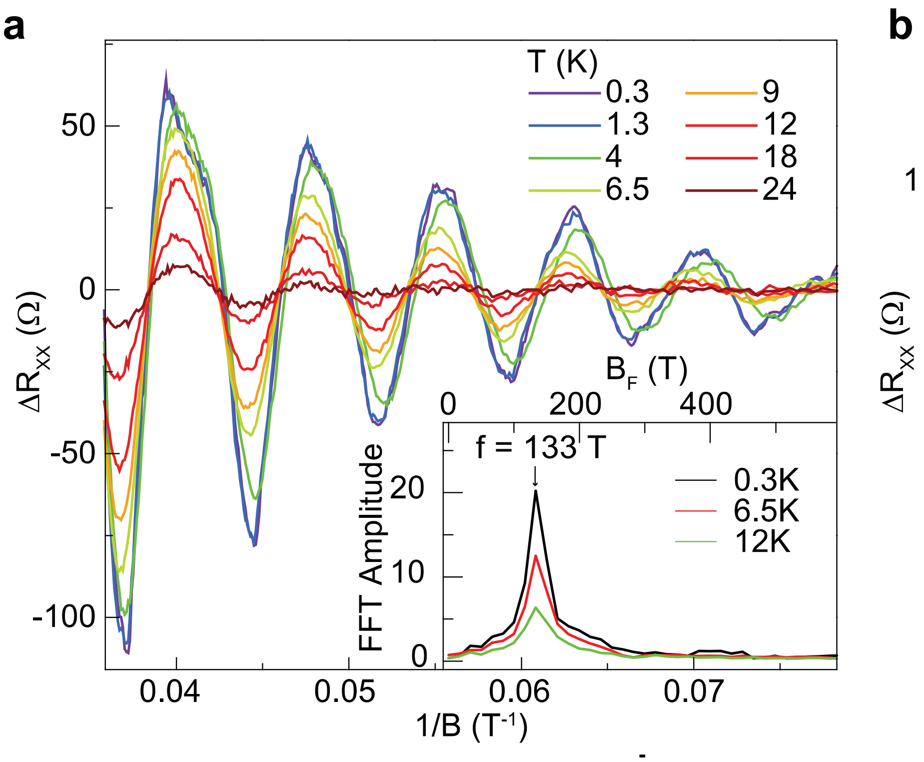


Prof. Yuanbo Zhang best mobility: ~6000 cm^2/V.s

More Temperature Dependence of SdH

Prof. Yuanbo Zhang

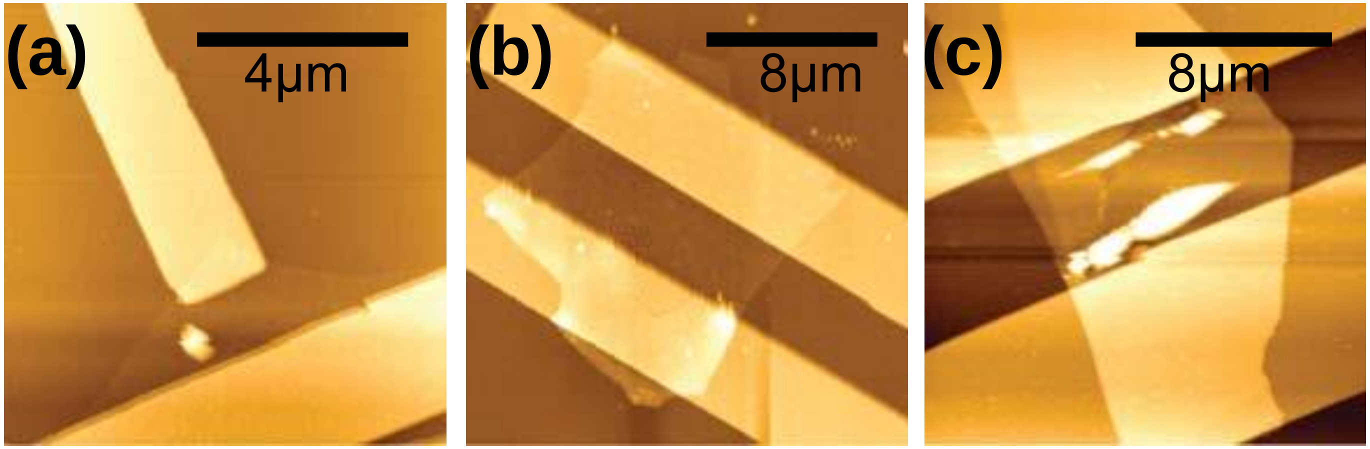




$m^{*}=0.34\ m_0$ $\Phi_B=0$

Nature Nanotechnology (2015)

Atomic Force Microscopy

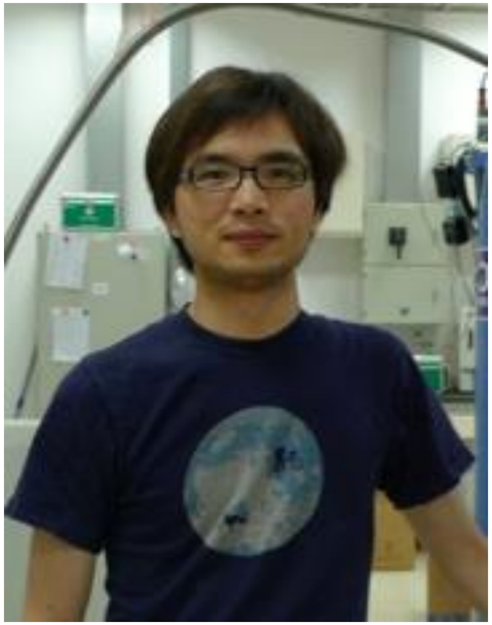


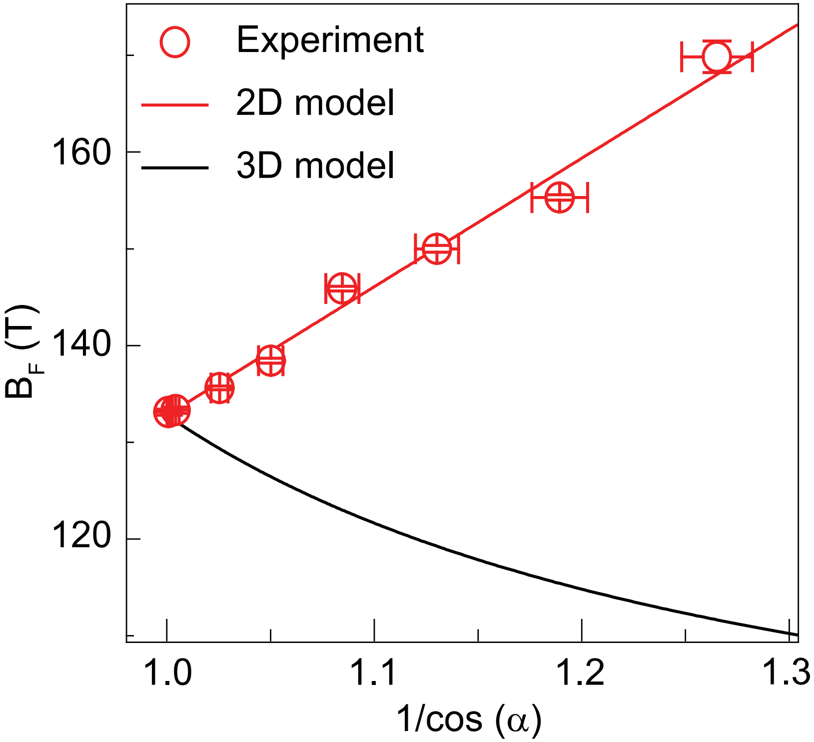
6±1 nm	12.5±1 nm	47±1 nm
11±2 layers	24±2 layers	90±2 layers

AFM performed *after* electrical transport measurements

2D Character from Angle-Resolved Data

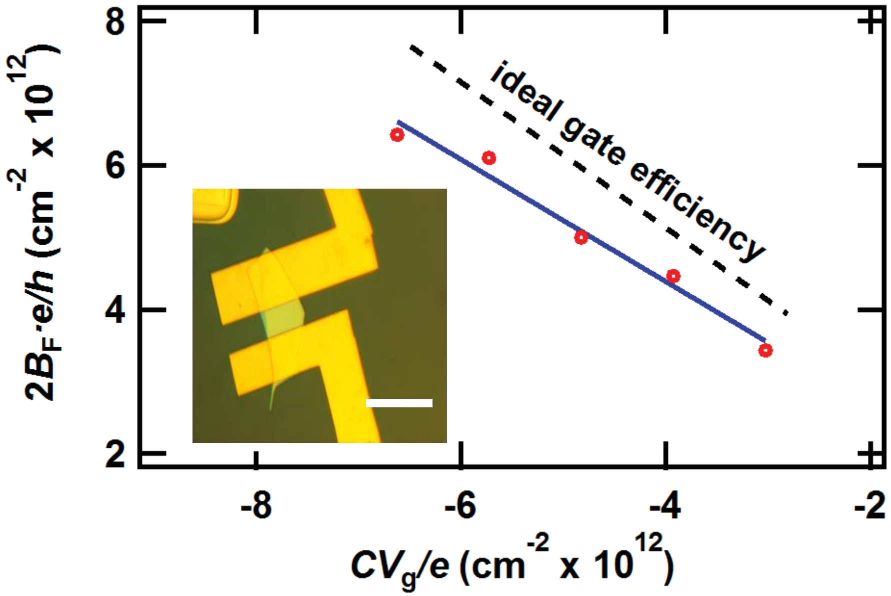
Prof. Yuanbo Zhang

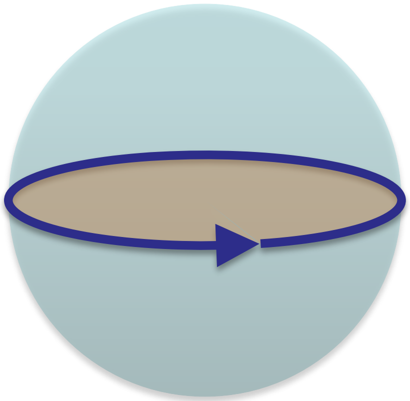




Nature Nanotechnology (2015)

Fermi Surface and Carrier Density





$$S_k = 4\pi^2 B_F \frac{e}{h}$$

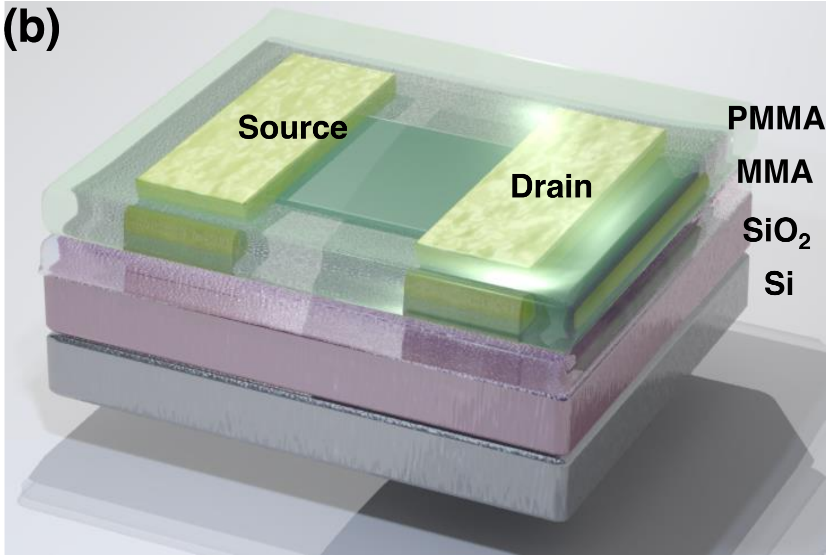
2D (Fermi disc) model:

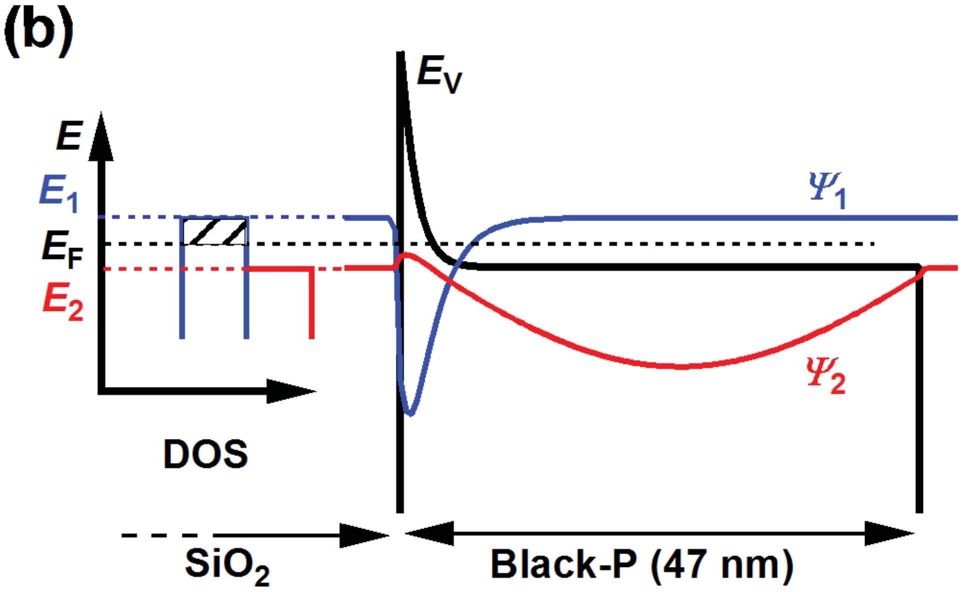
$$\frac{CV_G}{e} = n_{2D} = 2 \cdot B_F \cdot \frac{e}{h}$$

~~3D (Fermi sphere) model:~~

$$\cancel{\frac{CV_g}{e} = t \cdot n_{3D} = t \cdot \frac{8\sqrt{\pi}}{3} \left(B_F \cdot \frac{e}{h} \right)^{3/2}}$$

Schrödinger-Poisson *Simulation*





Self-consistent Schrödinger-Poisson simulation:

- 2D hole accumulation layer
- rms width 2.7nm ≈ 5 - 6 layers
- $E_1 - E_2$ = 28 meV sub-band confinement energy

V. Tayari, ………G. Gervais, R. Martel, T. Szkopek Nature Communications (2015