Non-classical Longitudinal Magnetoresistance in anisotropic black phosphorus

Francesca Telesio[1], Nicholas Hemsworth[2], William Dickerson[2], Mathei Patrescu[3], Vahid Tayari[2], Oulin Yu[3], David Graf[4], Manuel Serrano-Ruiz[5], Maria Caporali[5], Maurizio Peruzzini[5], Matteo Carrega[1], Thomas Szkopek[2], Stefan Heun[1] and Guillaume Gervais[3]

[1]NEST, Istituto Nanoscienze-CNR and Scuola Normale Superiore, I-56127 Pisa, Italy

[2]Department of Electrical and Computer Engineering, McGill University, Montreal, Quebec, H3A 2A7, Canada

[3]Department of Physics, McGill University, Montreal, Quebec, H3A 2T8, Canada

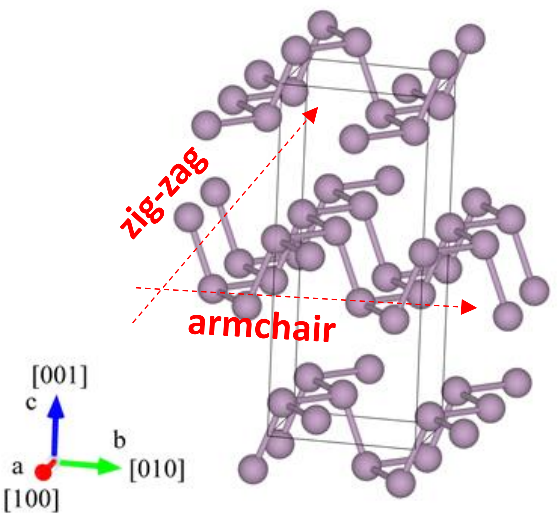
[4]National High Magnetic Field Laboratory, Tallahassee, FL 32310, United States

[5]Istituto Chimica dei Composti OrganoMetallici-CNR, I-50019 Sesto Fiorentino, Italy

August 2nd 2018, Montpellier, France

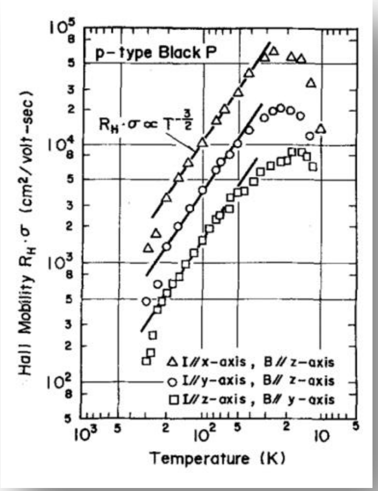
ICPS 2018 34th International Conference on the Physics of Semiconductors

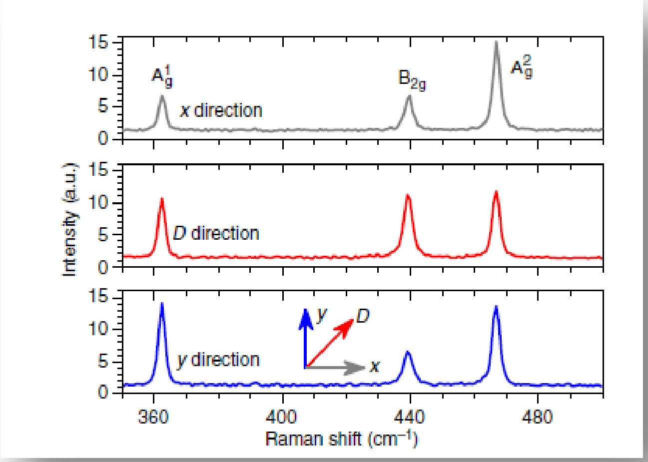
What is black phosphorus?



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

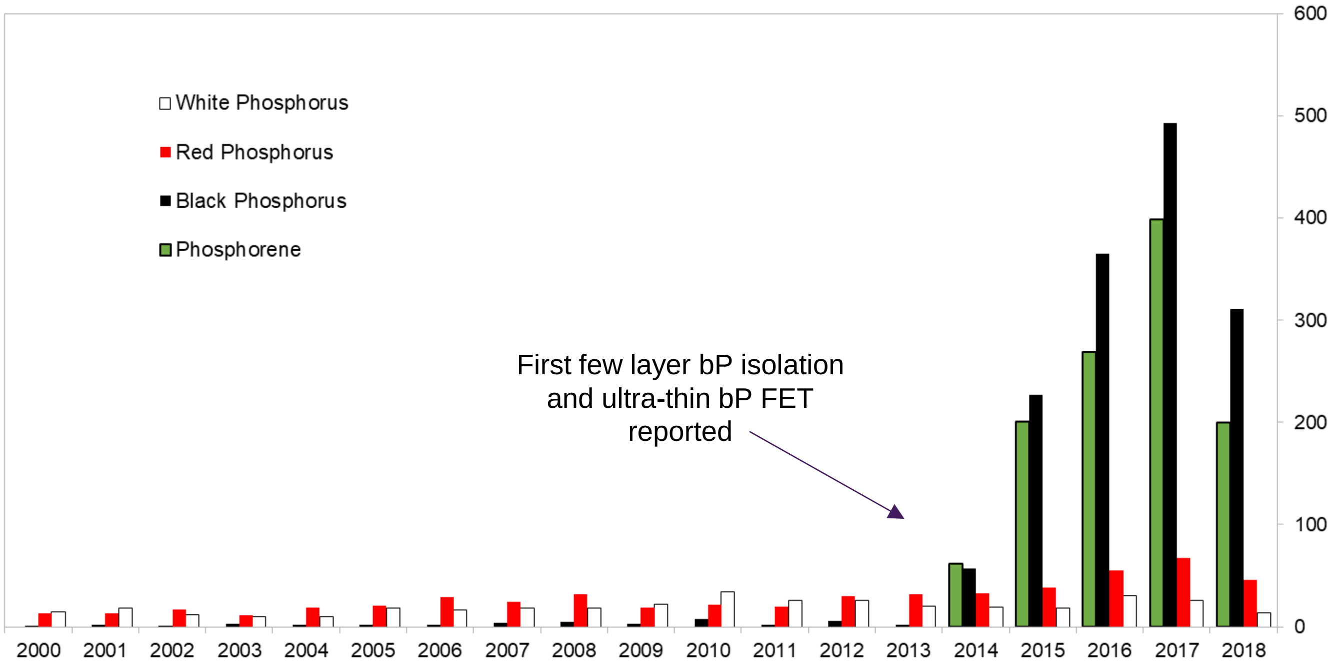
- ✓In 1914 first successful synthesis (Bridgman) and in 2007 synthesis at room pressure (Lange, Nilges)
- ✓Strong crystalline anisotropy in the plane
- ✓p-type semiconductor: 0.3eV direct band gap and high hole mobility (64,000 cm^2/Vs @ 20 K)
- ✓Vibrational modes of the crystal are Raman active





A. Morita, Appl. Phys. A 39 (1986),
A. Castellanos-Gomez et al, 2D Mat. 1, (2014); F. Xia et al, Nat Comm 5, (2014)

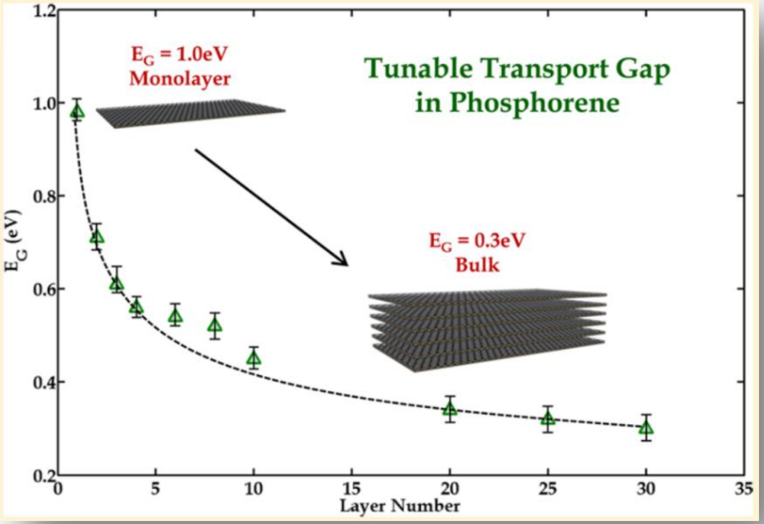
The renaissance of black phosphorus



A. Castellanos-Gomez et al, 2D materials 1, (2014); L. Li et al, Nature Nanotech. 9 (2014) (Y. Zhang group);
H. Liu et al., ACS Nano 8 (2014) (P. Ye group); N. Gillren at al., 2D Materials 2, (2014) (J. Lau group);
X. Chen et al Nat. Comm. 6 (2015) (N. Wang group)

The renaissance of black phosphorus

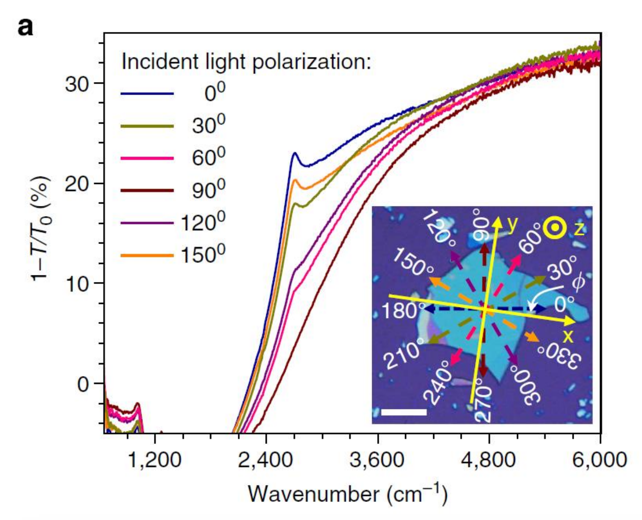
- ✓ Direct band-gap tunable with layer number

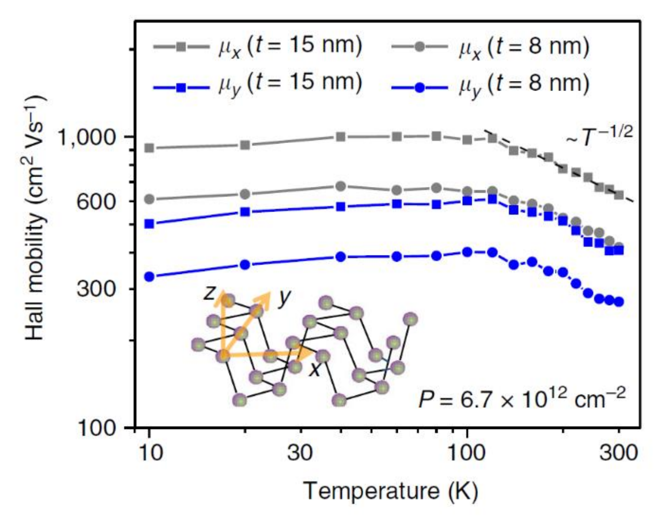


S. Das et al., Nano Lett. 14 (2014)

The renaissance of black phosphorus

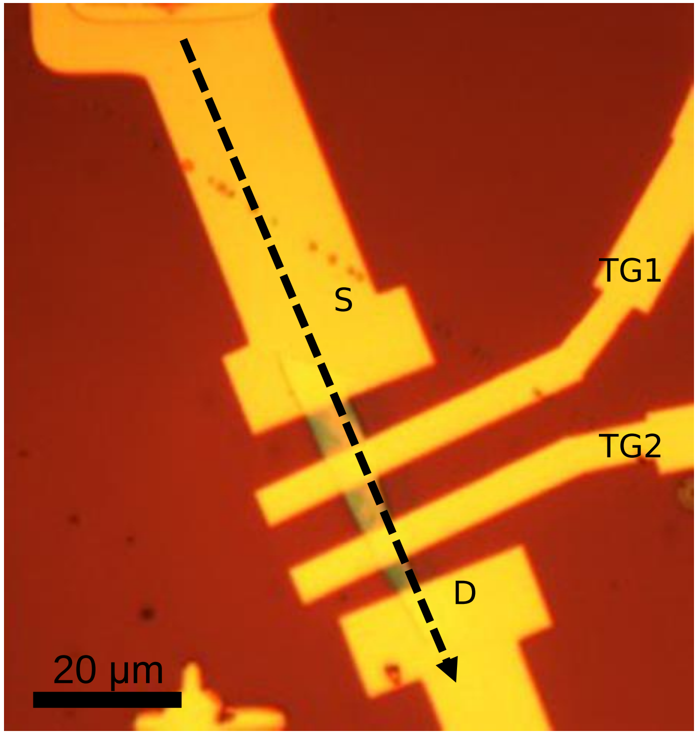
- ✓Direct band-gap tunable with layer number
- ✓In-plane anisotropy of optical and electrical and thermal transport properties





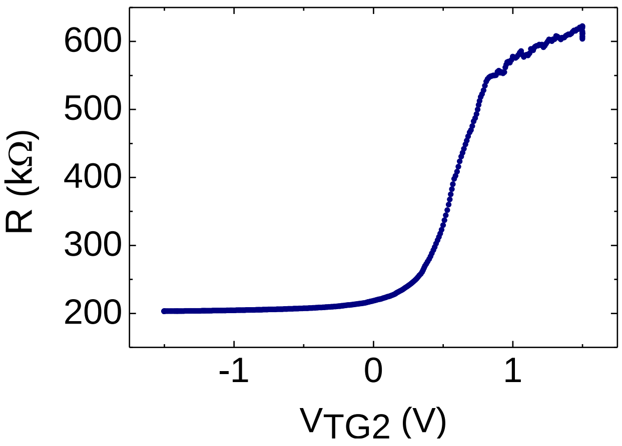
F. Xia et al., Nat. Comm. 5 (2014)

bP FET device



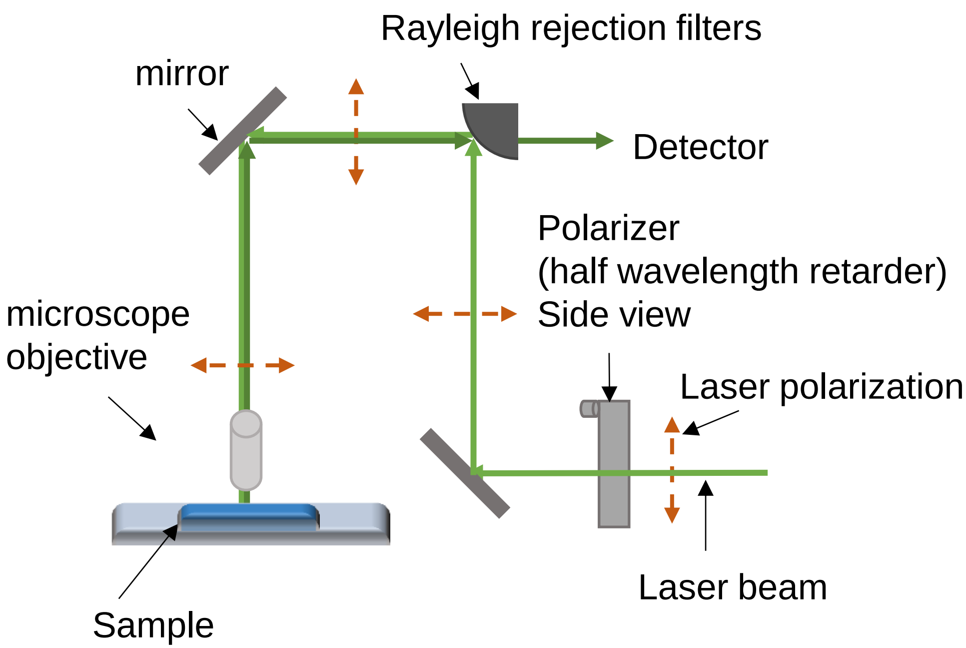
- (16±1) nm thick bP flake
- Two top gates TG1 and TG2 fabricated with a combination of PO_x and Al_2O_3 [1]

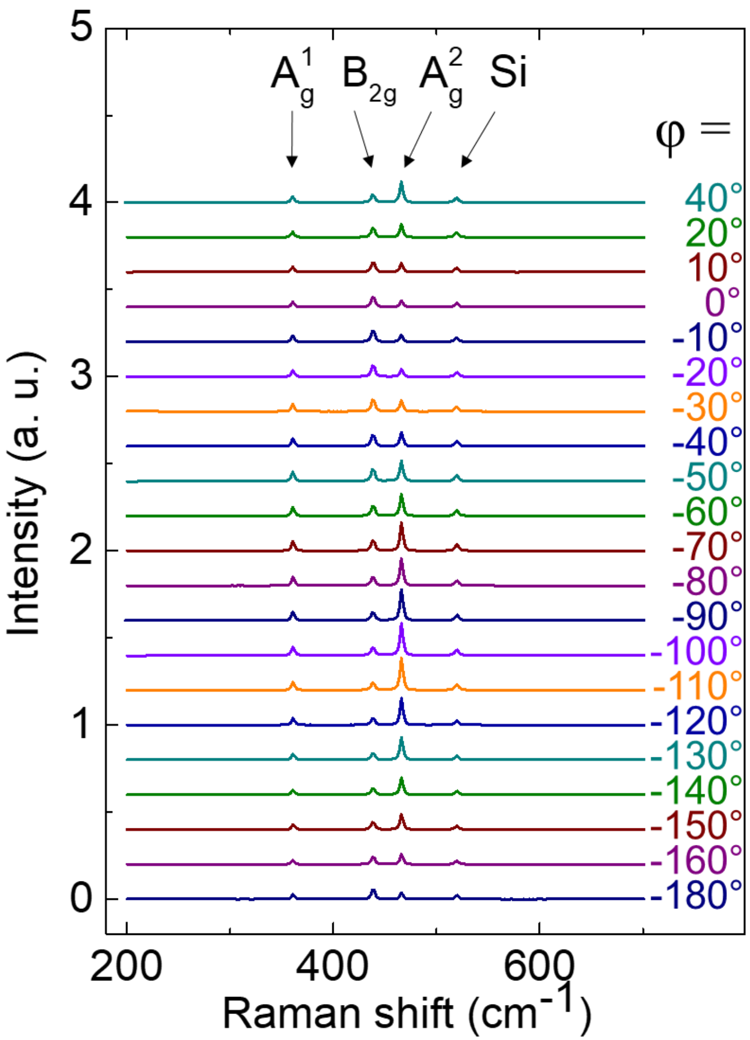
- n=2.2 10^{12} cm^{-2} and µ=83 $cm^2/(Vs)$ at 1.5 K, 11.4 T



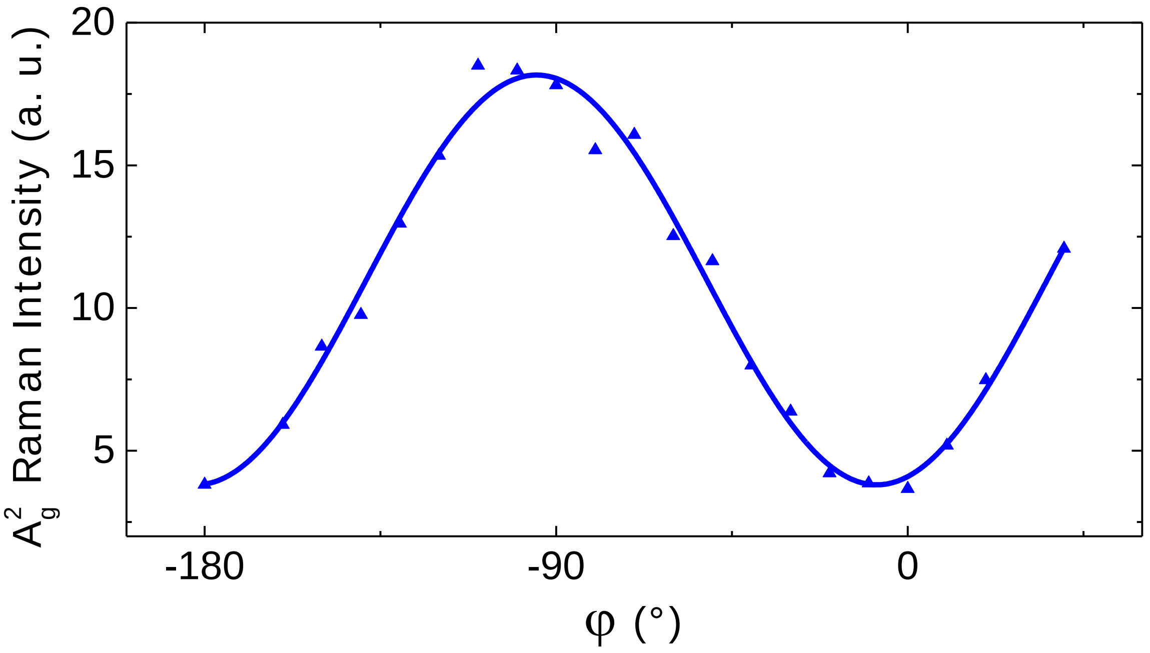
[1] W. Dickerson et al., APL 112, (2018)

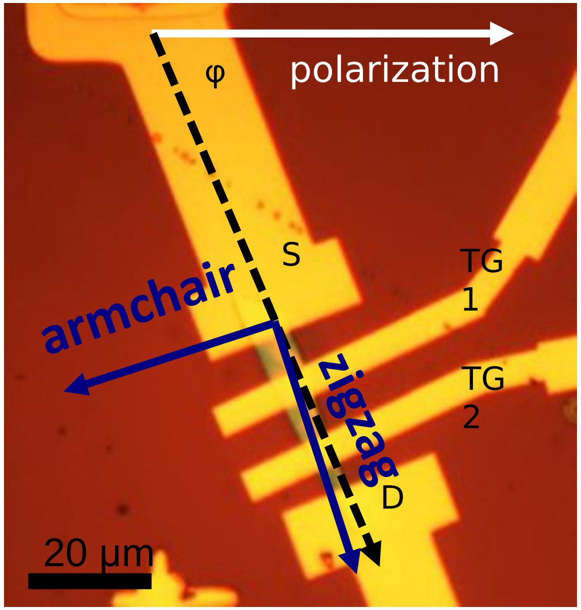
Crystal orientation: polarized Raman





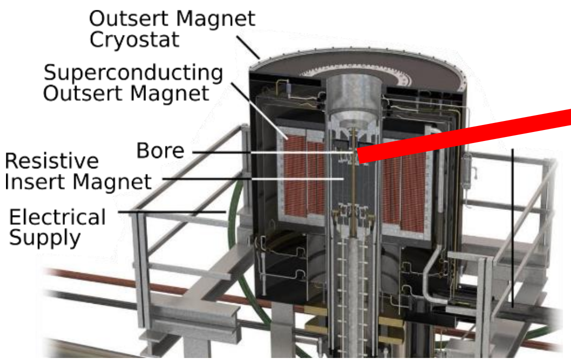
Crystal orientation: polarized Raman

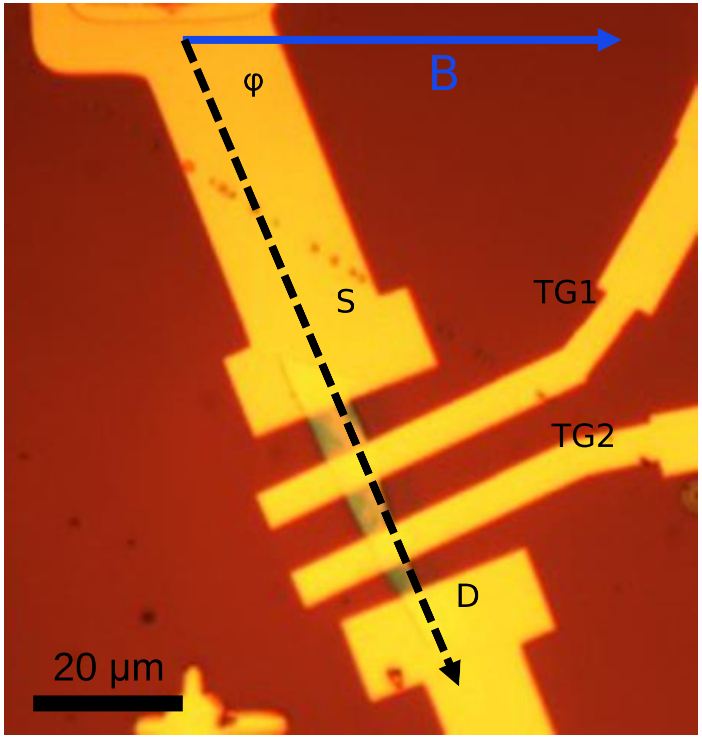




In plane magnetotransport: the experimental setup.

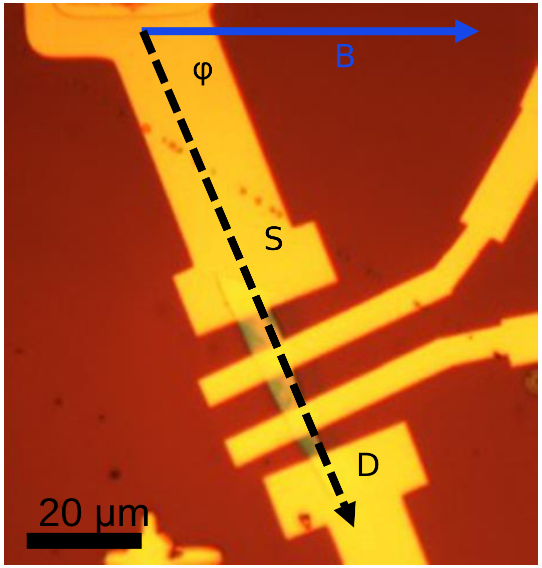
Hybrid 45 T magnet Tallahassee, USA

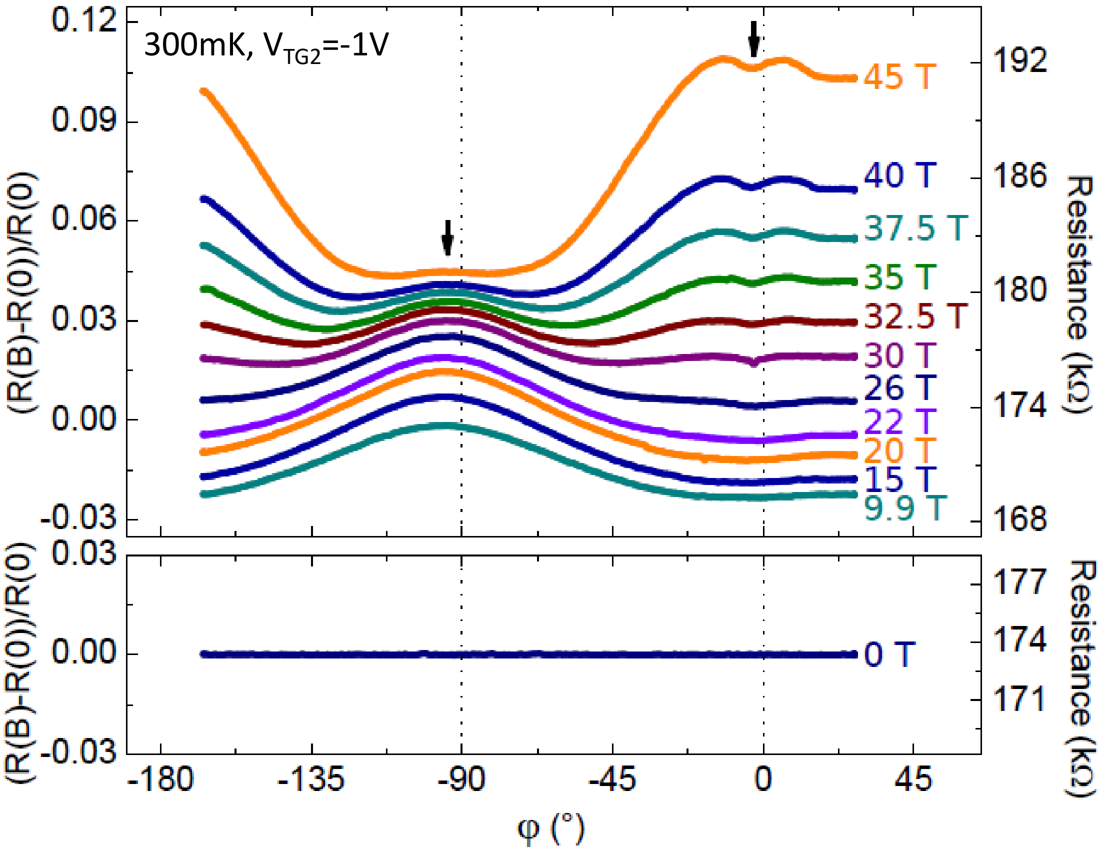




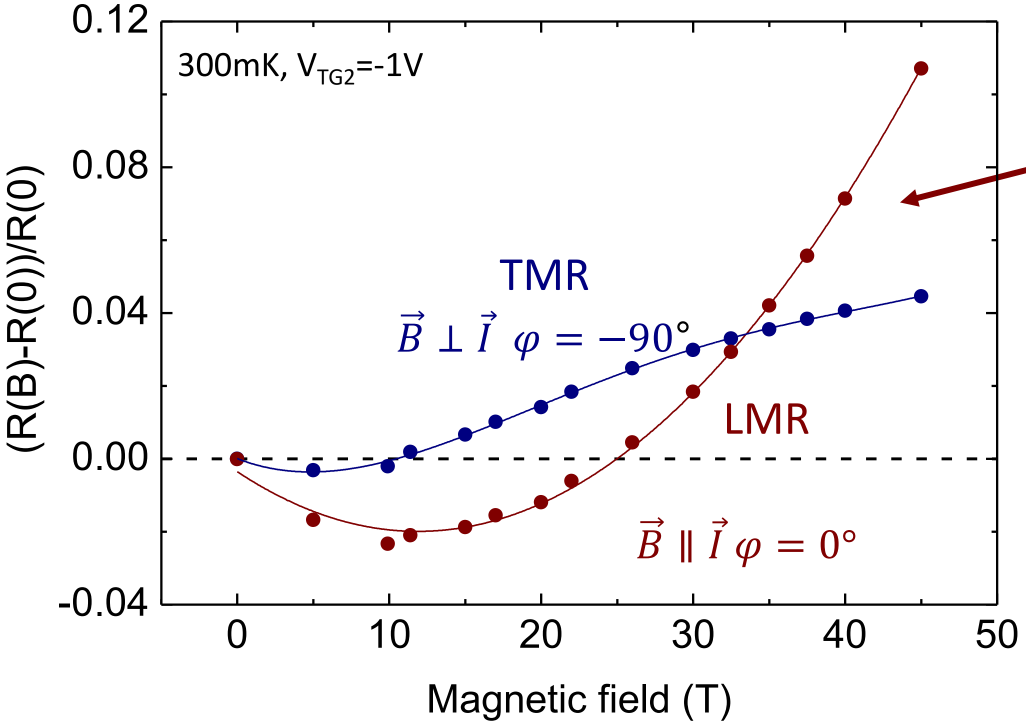
The sample is mounted on a rotator and it rotates in the plane of magnetic field.

In plane magnetotransport



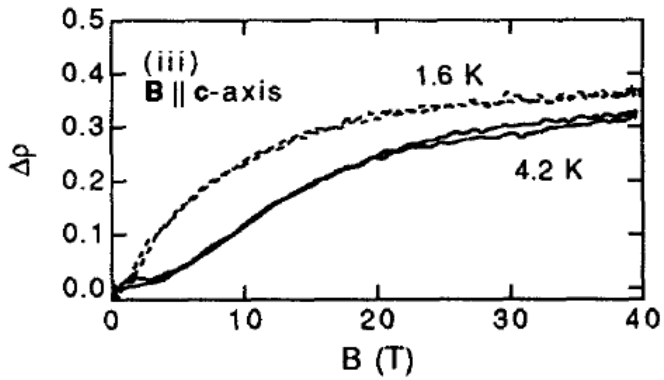


In plane magnetotransport



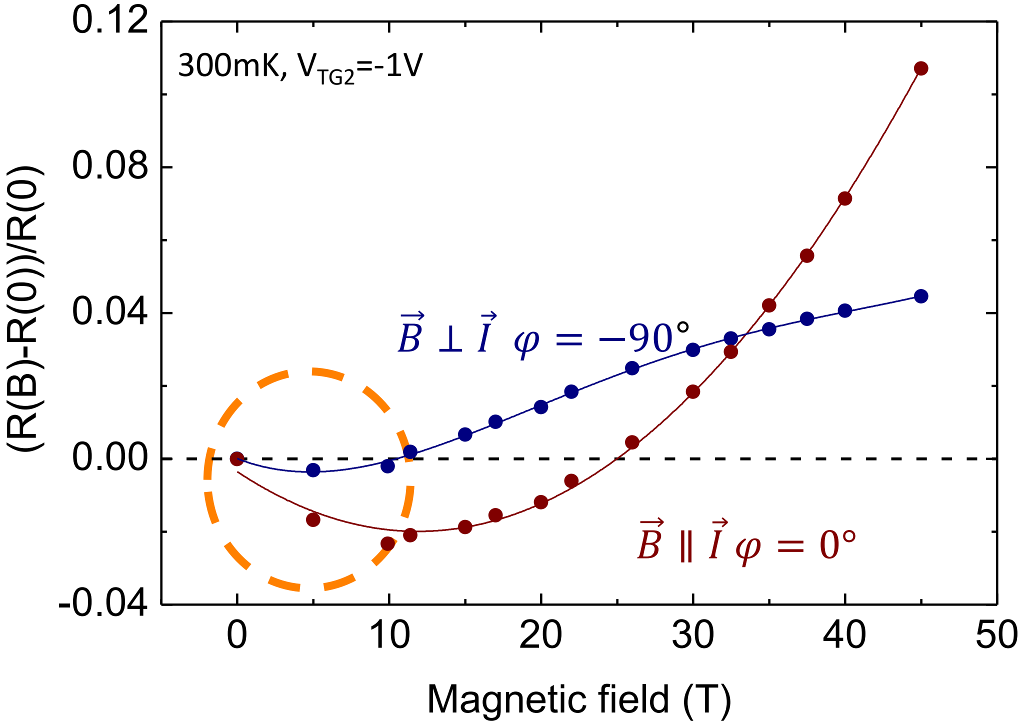
The conventional model based on Lorentz force cannot produce longitudinal magnetoresistance LMR, since $\vec{v} \parallel \vec{B}$

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$



Strutz et al, Physica B, 194, (1994)

In plane magnetotransport: low field regime



- bP has an elliptical fermi surface in the plane

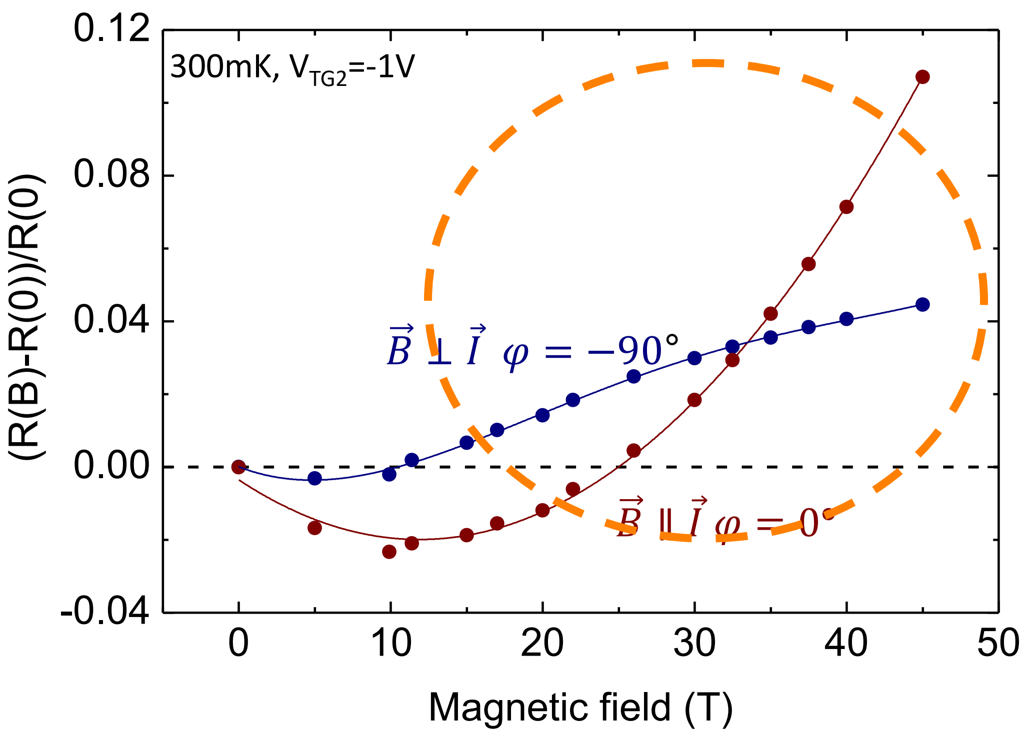
$$le_{zz} = 3.2\ nm$$

$$\alpha = le_{zz}k_{Fzz} = 1.9\ \rightarrow\ \text{close to localization}$$

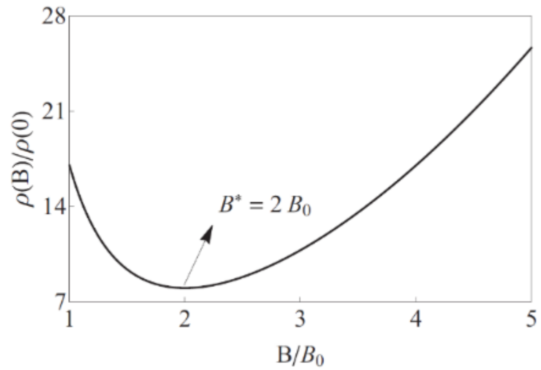
- Consistent with previous literature on disordered/localized bP [2]

[2] N. Iwasaki er al, Chemistry Letters 14, (1985); T.-H. Lee et al , Phys. Status Solidi RRL 10, (2016), S. J. Choi er al, Nano Letters, 16, (2016), G. Long er al Nanotechnology 29, (2018) ; N. Hemsworth et al, PRB 92 (2016)

In plane magnetotransport: high field regime



- LMR can arise in case of Fermi surface anisotropy (Pal and Maslov, PRB 88, (2010))
- Its sign can be negative or positive (and it can change) for different scattering mechanisms, from short range to long range scattering



Goswami, Pixley
and Das Sarma, PRB 92, (2015)

- This picture still holds in a semiclassical regime (Son and Spivak, PRB 88 (2016))

Conclusions

- We measured **in-plane magnetoresistance** of a bP FET
- The observed behavior was **strongly anisotropic**
- Negative magnetoresistance at low field is consistent with previous experiments
- **Positive Longitudinal magnetoresistance** is observed at high field
- **Fermi surface anisotropy**, with the field rotating in the plane where anisotropy is pronounced, plays a crucial role in explaining the phenomenon

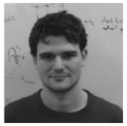
S.Heun

M. Carrega

N. Hemsworth

W. Dickerson

V. Tayari



M. Petrescu

Oulin Yu

G. Gervais

T. Szkopek

D. Graf

M. Caporali

M. Serrano-Ruiz

M. Peruzzini

*“**Phos**phorene **fun**ctionalization: a new platform for advanced multifunctional materials” (Grant Agreement No. 670173)*

Thank you for your attention!