Non-classical Longitudinal Magnetoresistance in anisotropic black phosphorus

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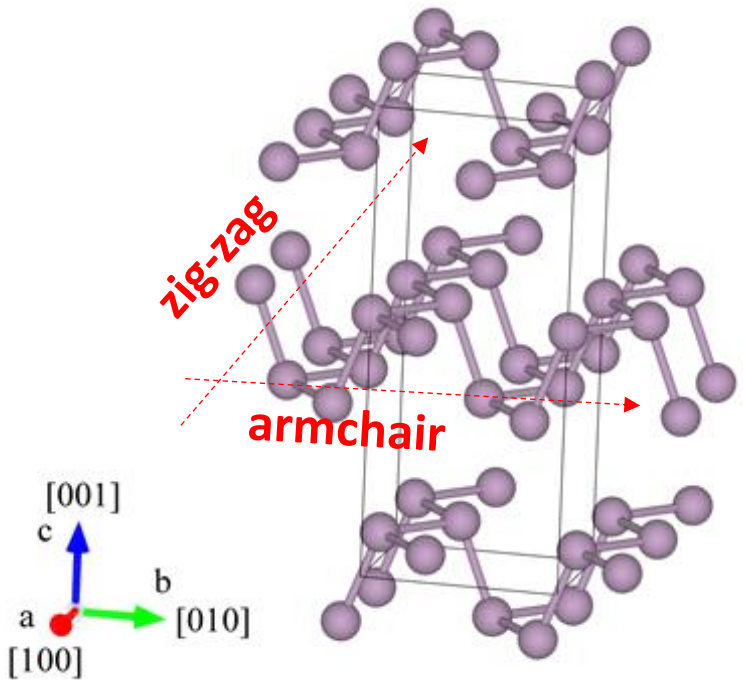
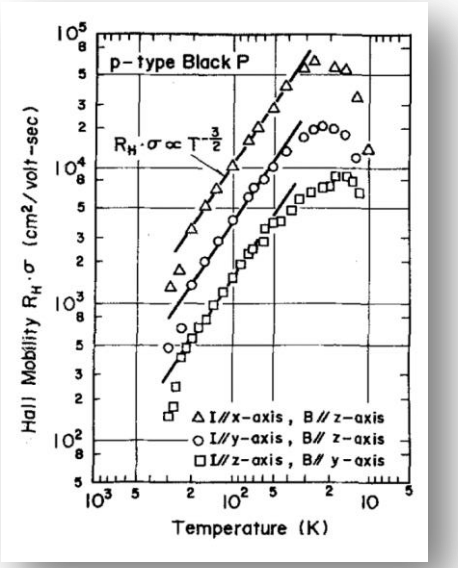
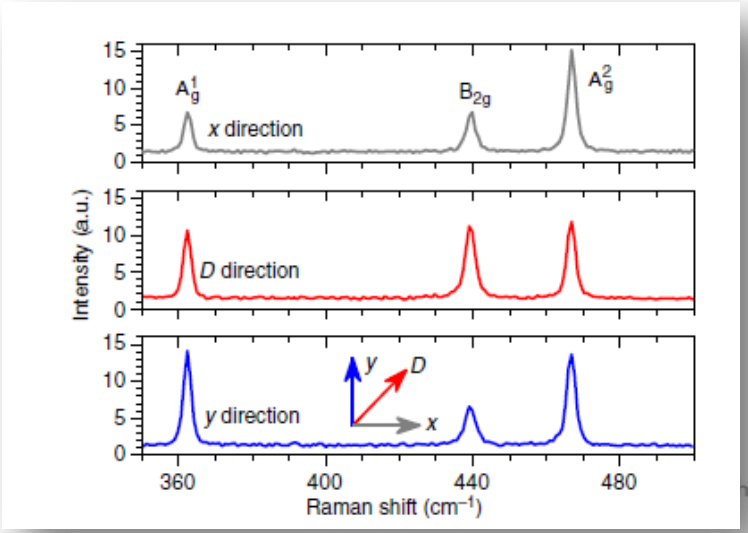
What is black phosphorus?



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

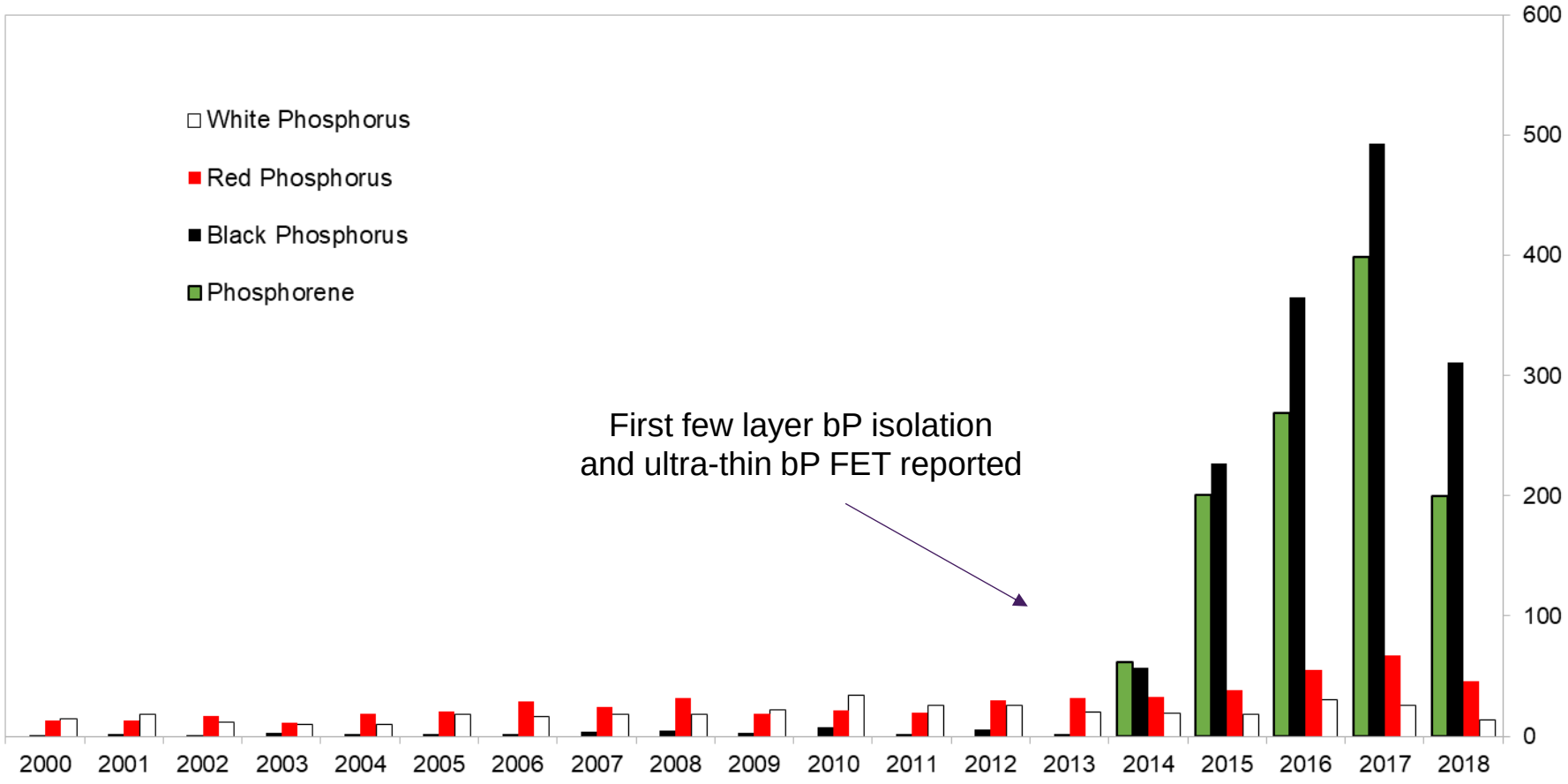
- ✓In 1914 first successful synthesis (Bridgman) and in 2007 synthesis at room pressure (Lange, Nilges)
- ✓Strong crystalline anisotropy in the plane
- ✓p-type semiconductor: 0.3eV direct band gap and high hole mobility (64,000 cm^2/Vs @ 20 K)
- ✓Vibrational modes of the crystal are Raman active





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

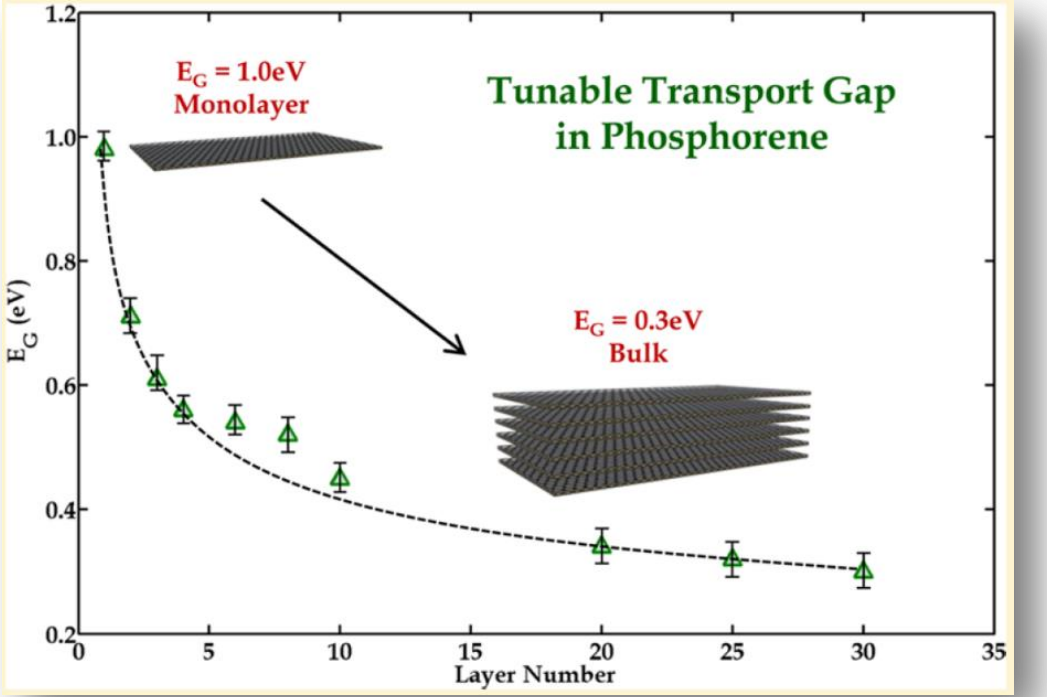
The renaissance of black phosphorus



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

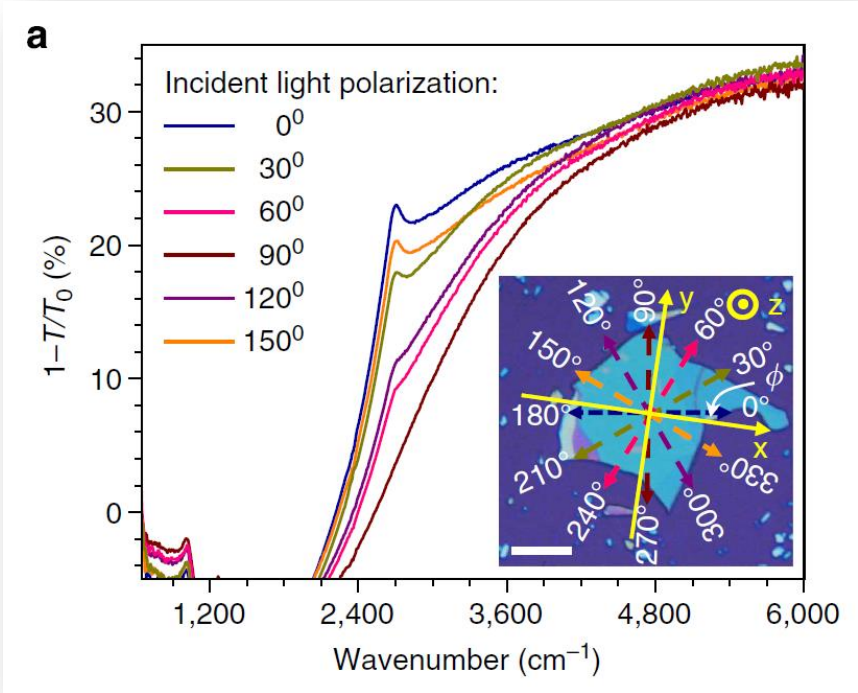
- ✓Direct band-gap tunable with layer number

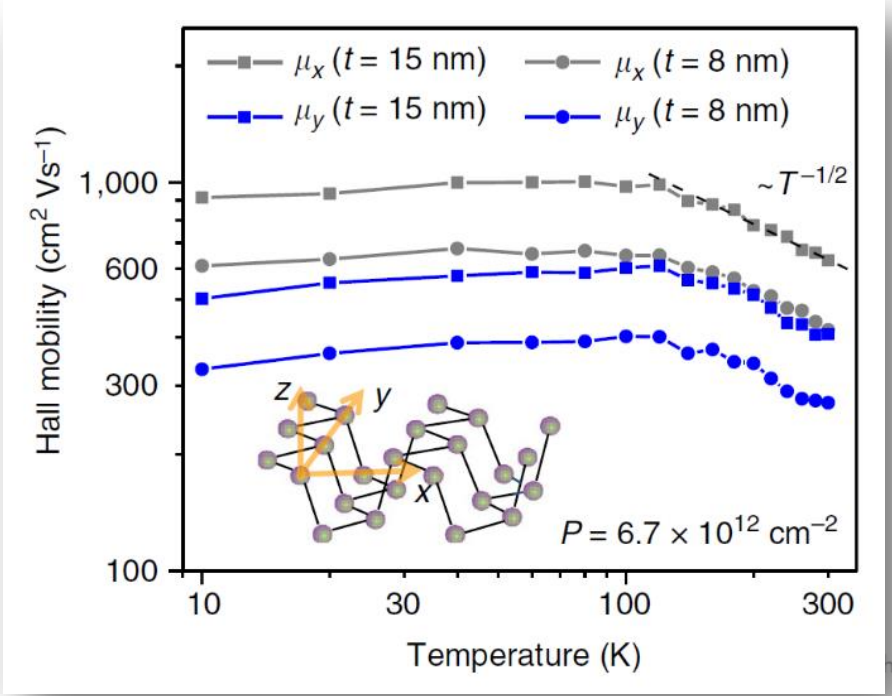


S. Das et al., Nano Lett. 14 (2014)

The renaissance of black phosphorus

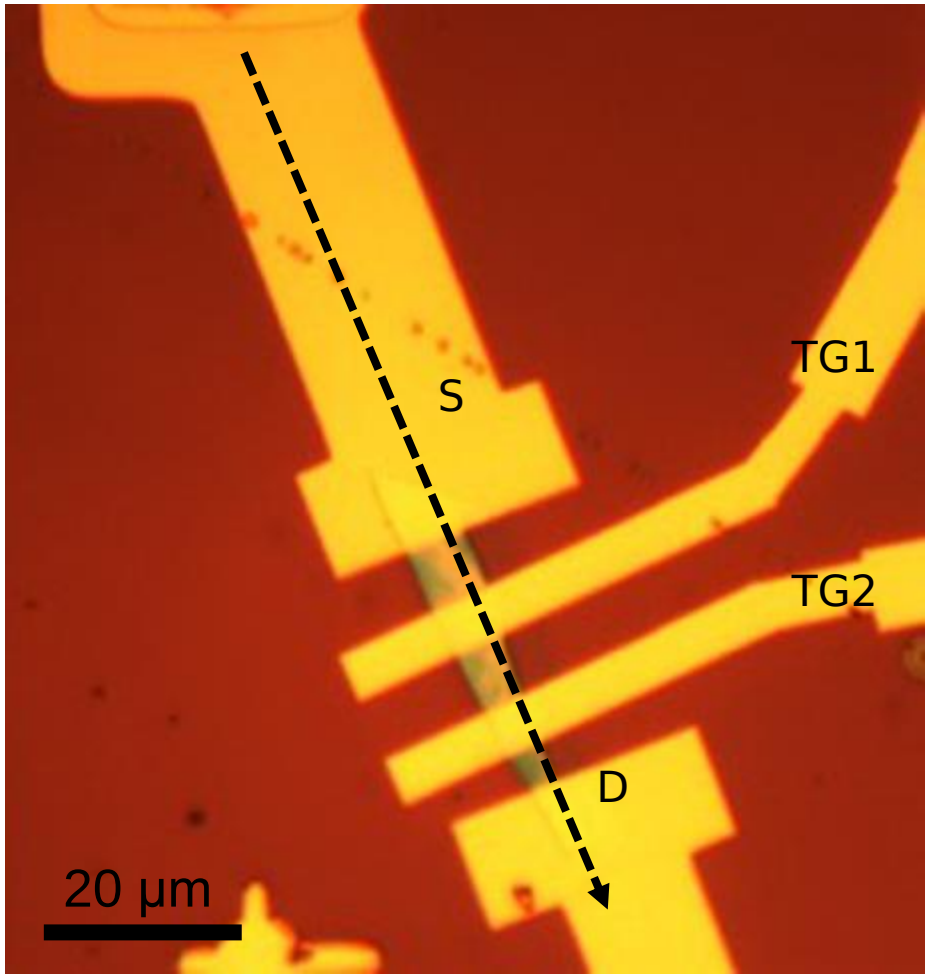
- ✓Direct band-gap tunable with layer number
- ✓In-plane anisotropy of optical and electrical and thermal transport properties



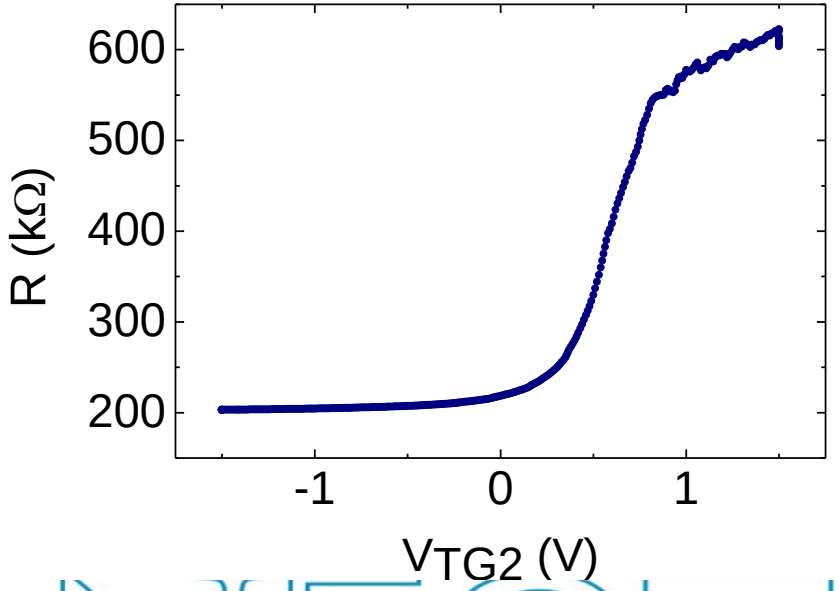


F. Xia et al., Nat. Comm. 5 (2014)

bP FET device

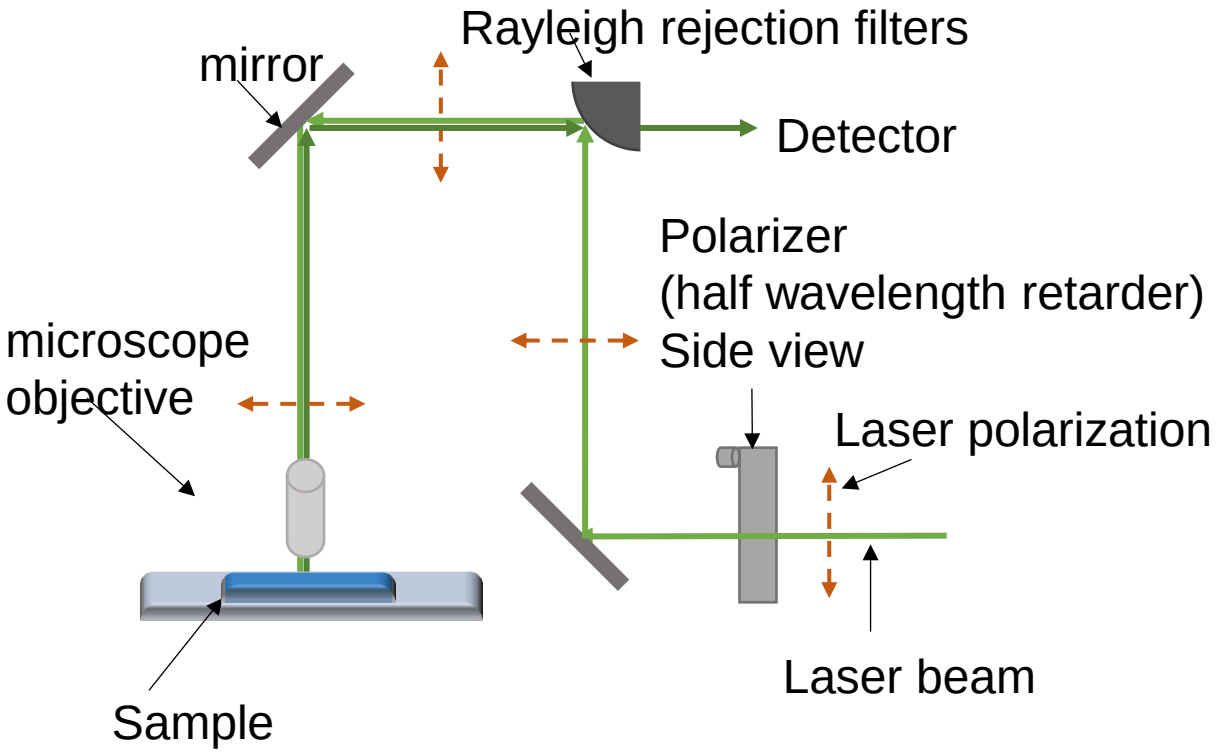


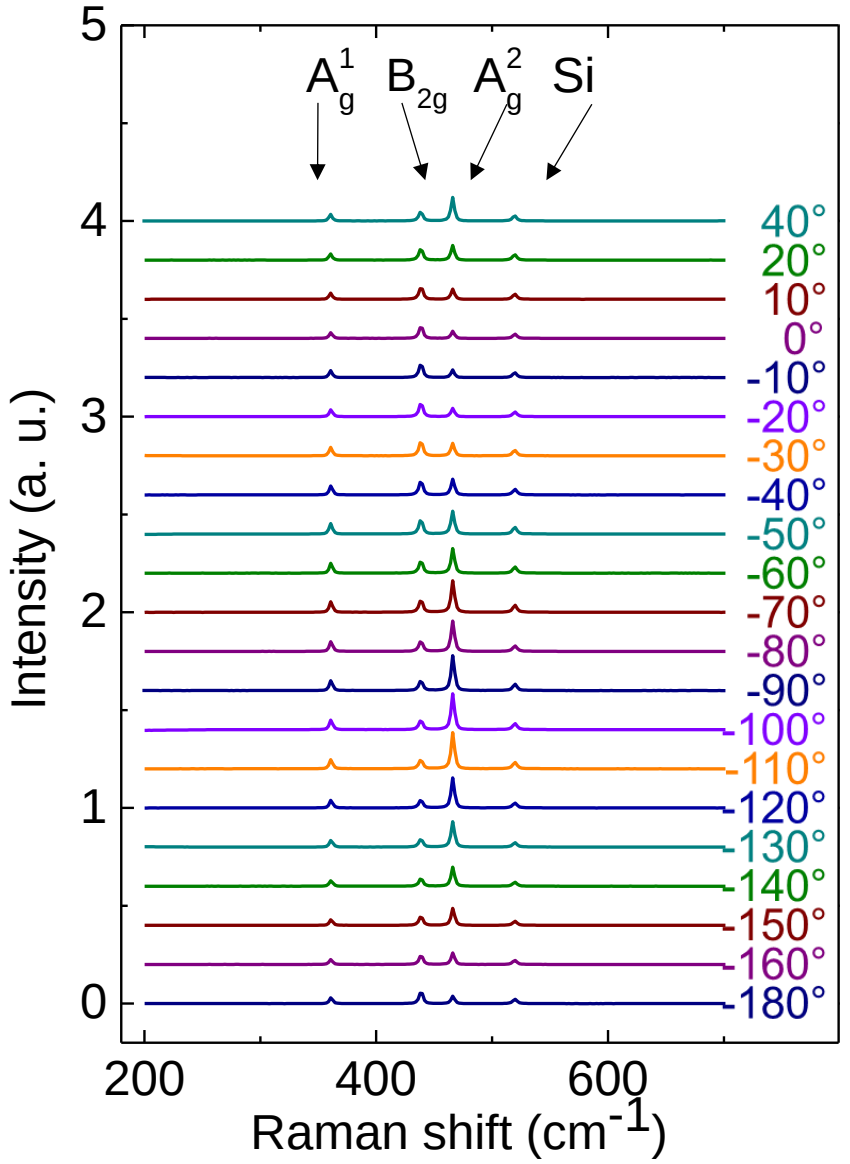
- (16±1) nm thick bP flake
- Two top gates TG1 and TG2 fabricated with a combination of PO_x and Al_2O_3 [1]
- n=2.2 10^{12} cm^{-2} and µ=83 $cm^2/(Vs)$ at 1.64 K, 11.4 T



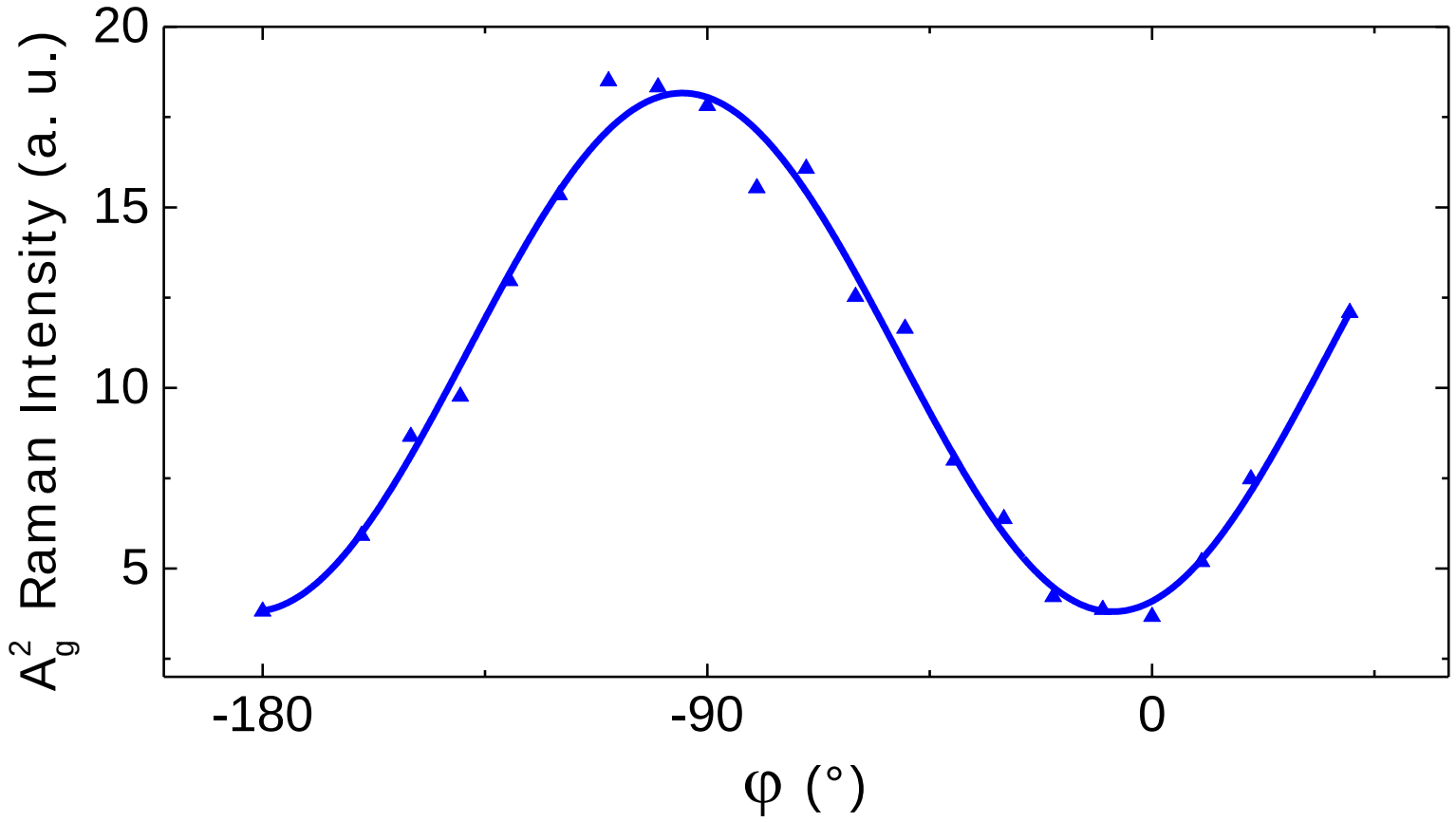
[1] W. Dickerson et al., APL 112, (2018)

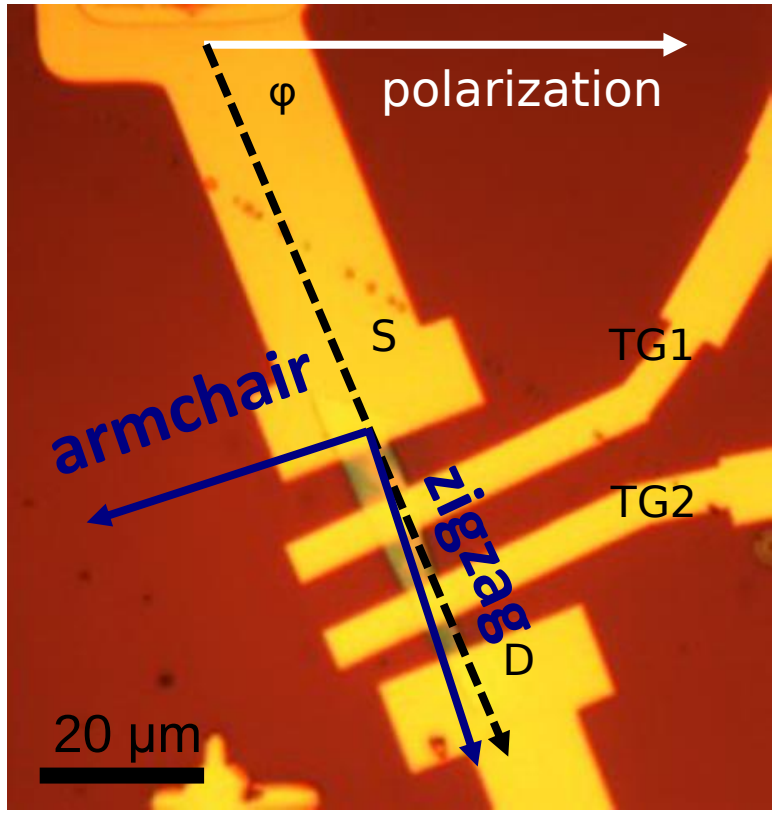
Crystal orientation: polarized Raman





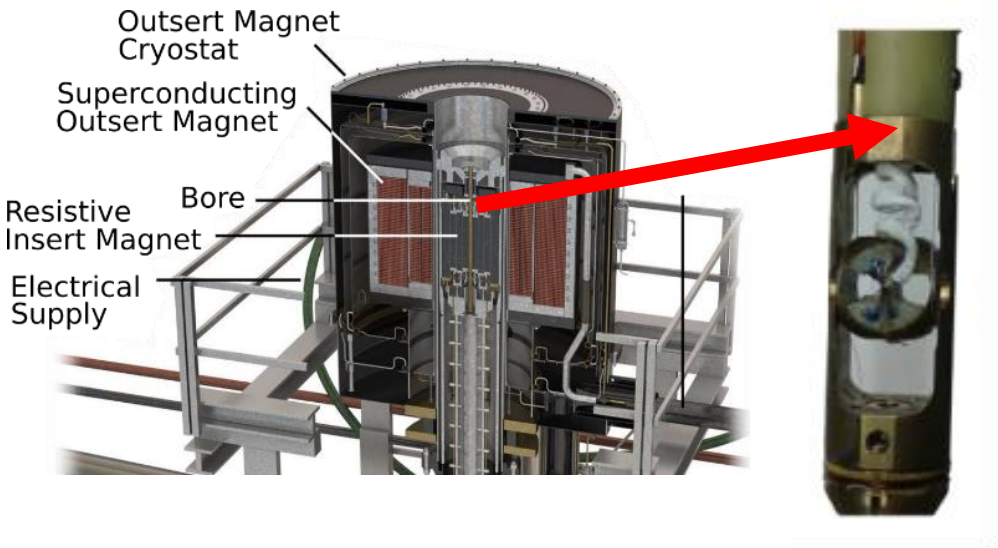
Crystal orientation: polarized Raman



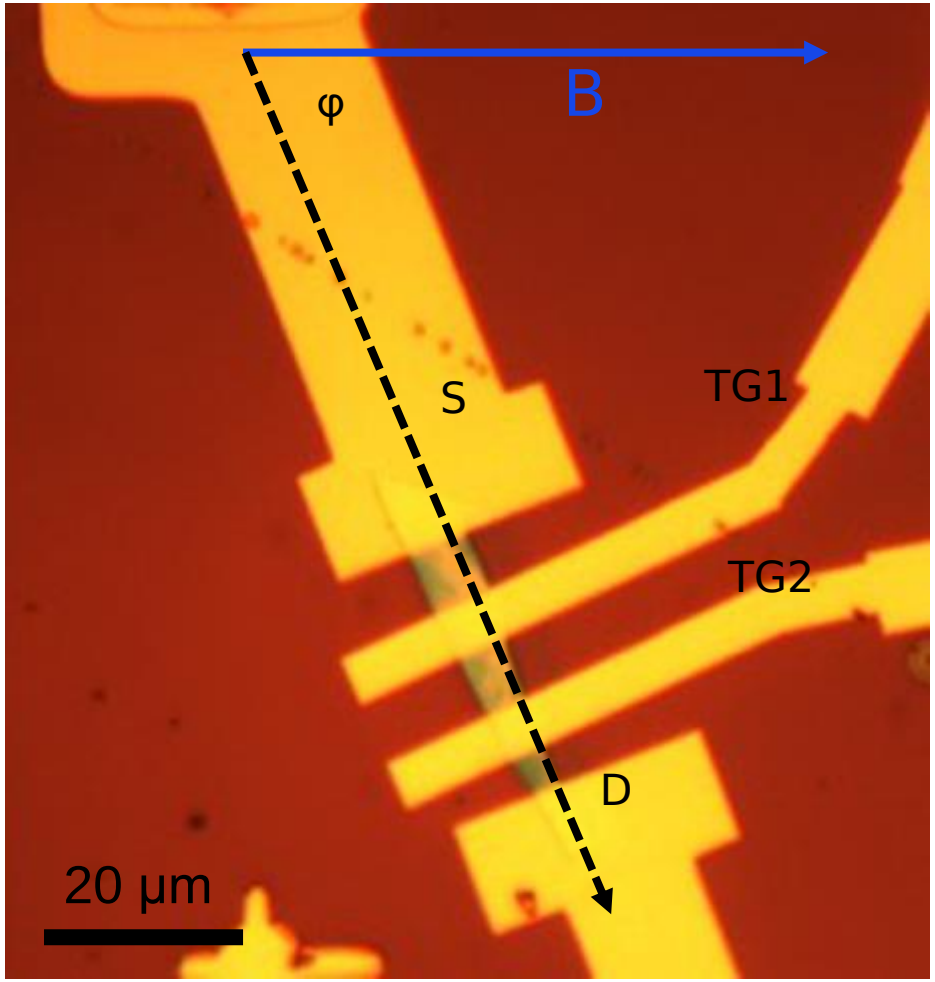


In plane magnetotransport: the experimental setup.

Hybrid 45 T magnet Tallahassee, USA



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



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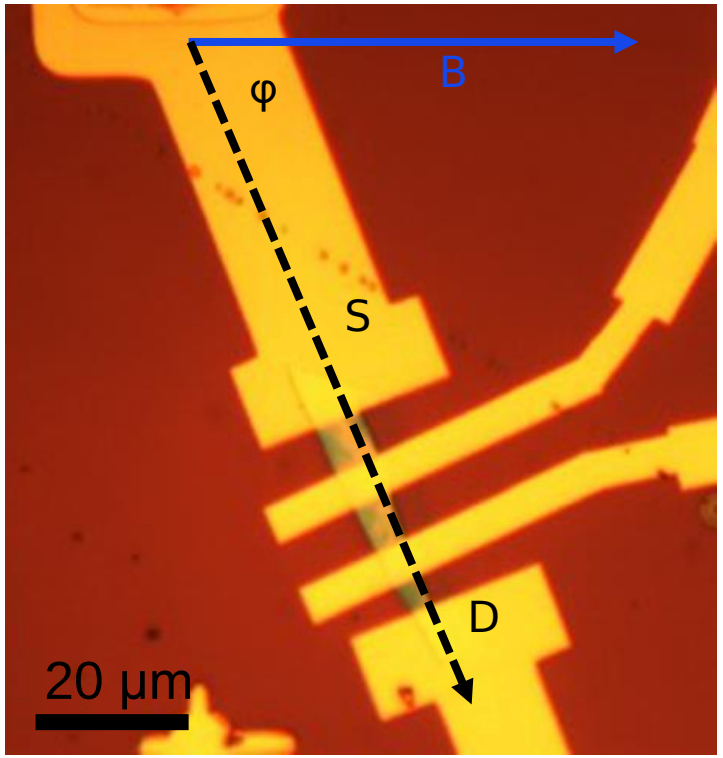

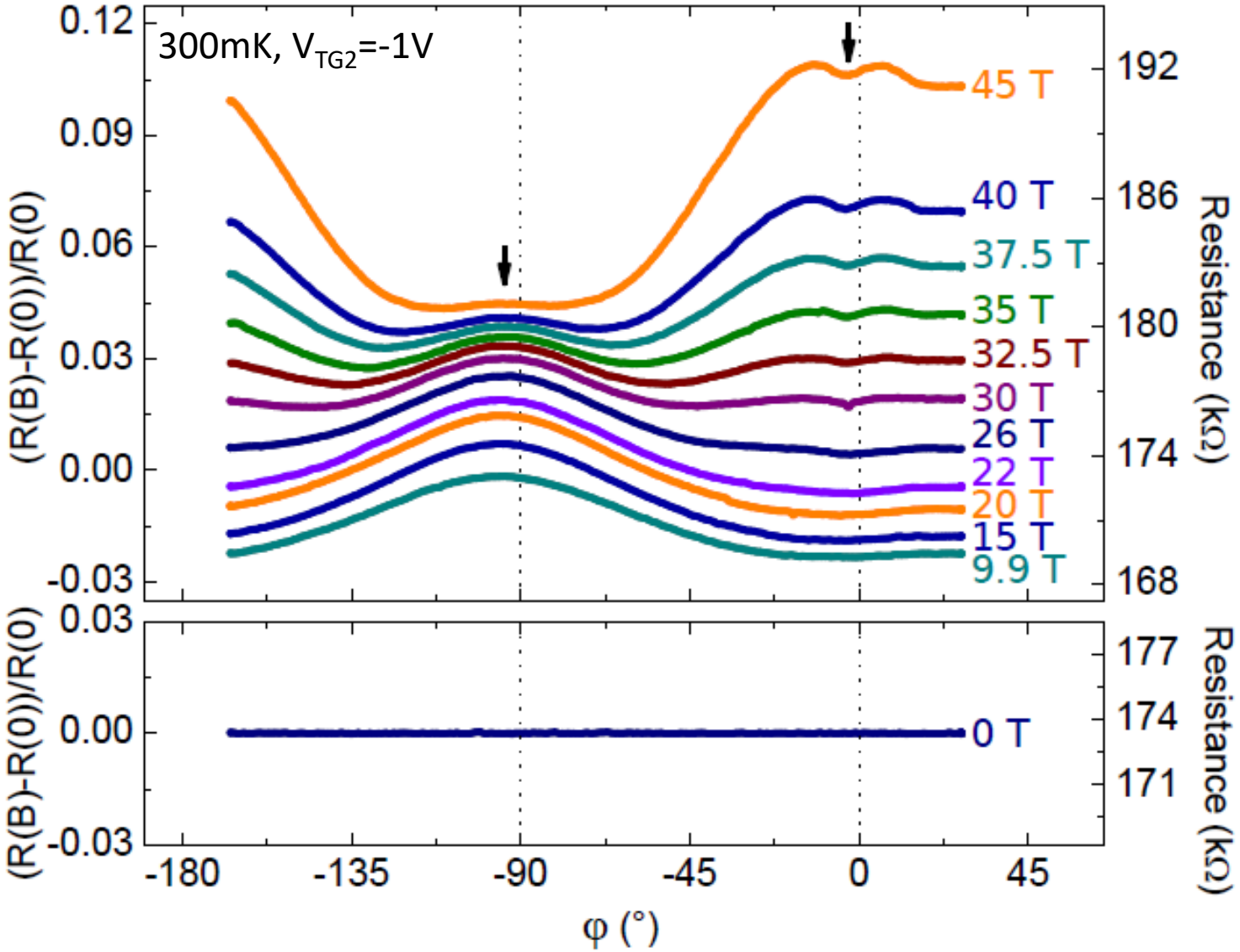

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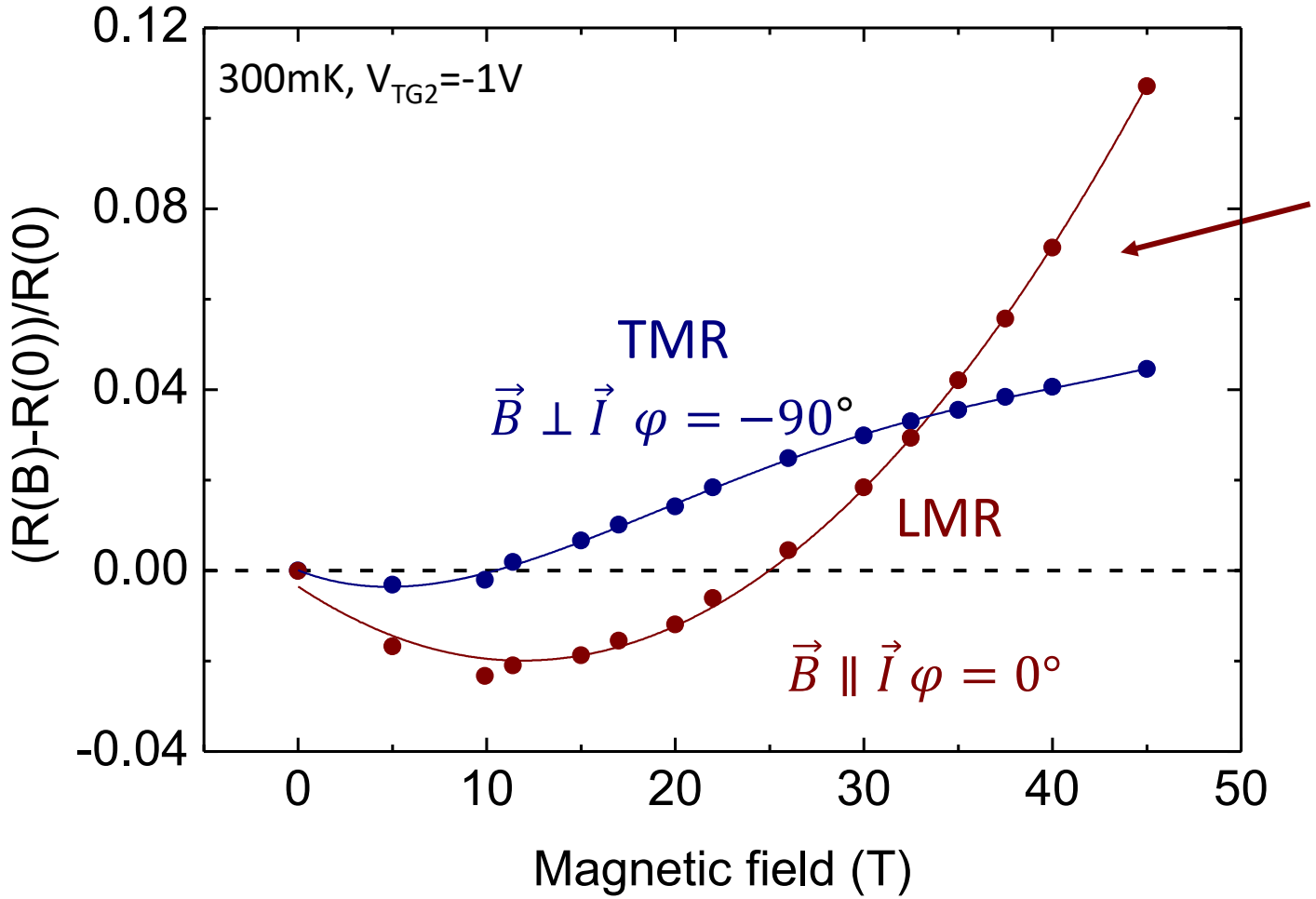
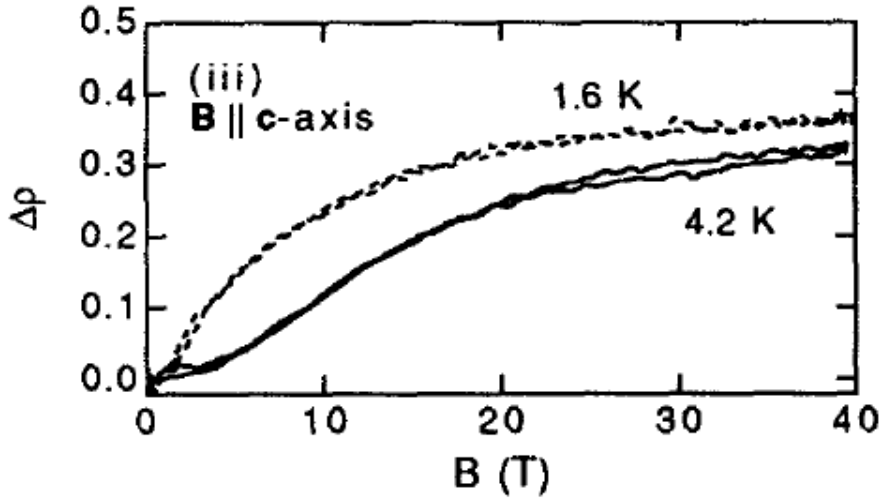


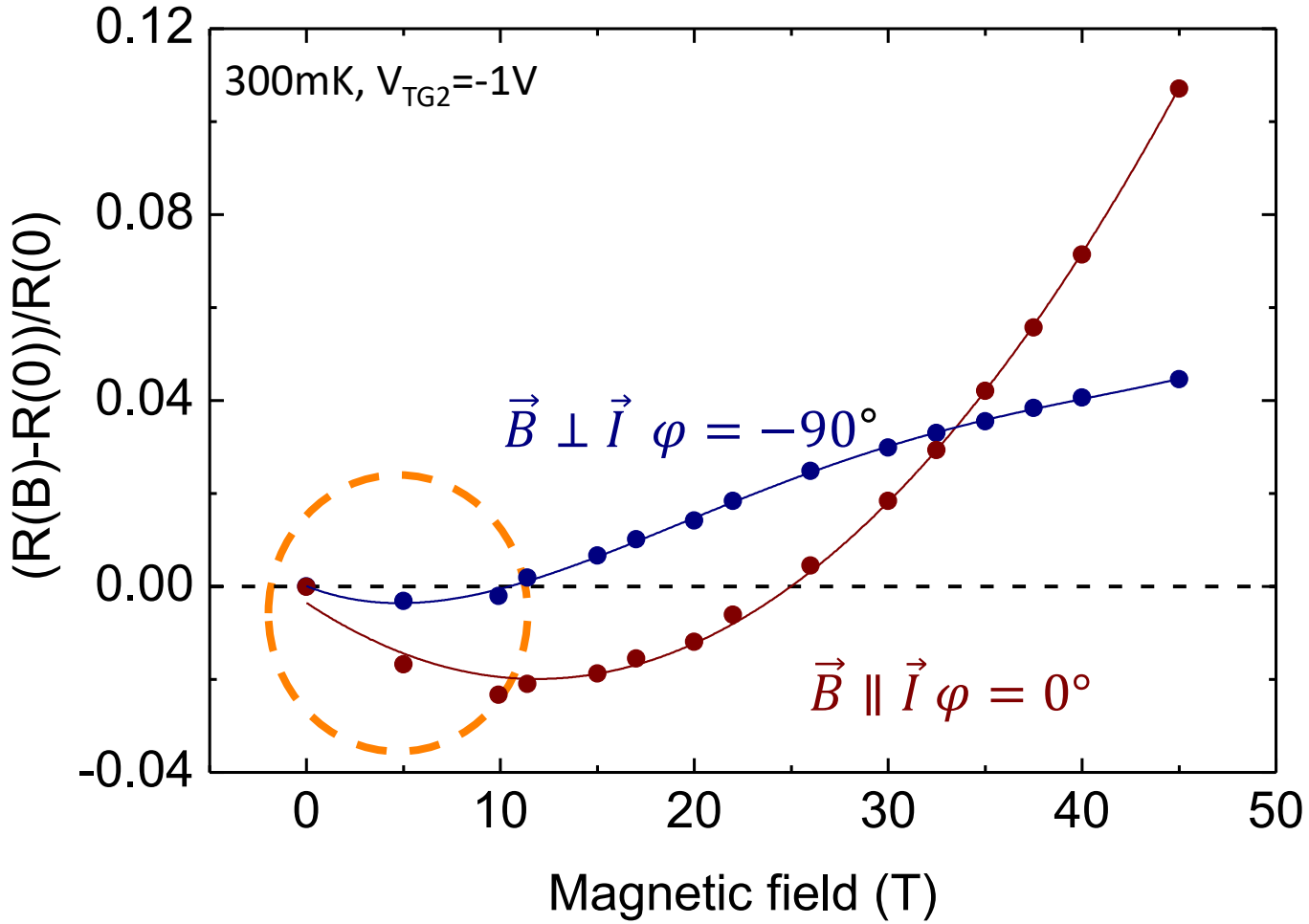
The conventional model based on Lorentz force cannot produce longitudinal magnetoresistance LMR, since $\vec{v} \parallel \vec{B}$

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



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

In plane magnetotransport: low field regime



- bP has an elliptical fermi surface in the plane

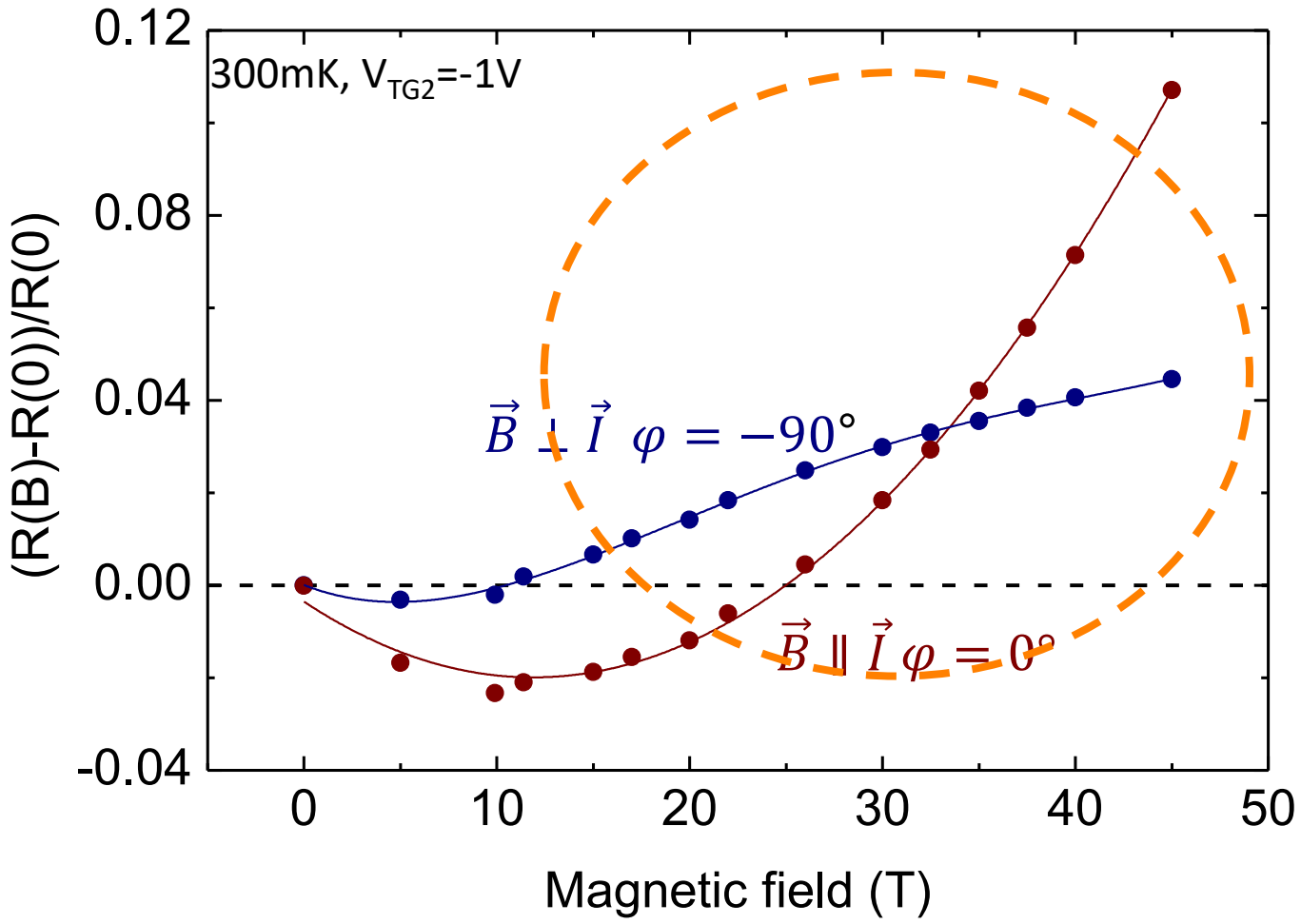
$$le_{zz} = 3.2\ nm$$

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

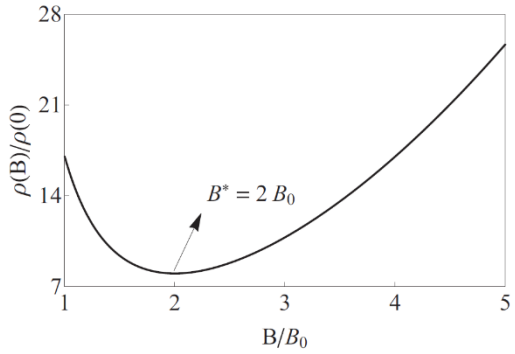
- Consistent with previous literature on disordered/localized bP [2]

[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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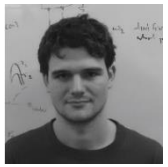
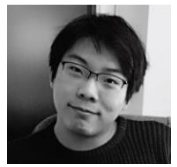
N. Hemsworth


W. Dickerson


V. Tayari


M. Petrescu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Thank you for your attention!

National Enterprise for nanoScience and nanoTechnology