Non-Classical Longitudinal Magneto-Resistance in Anisotropic Black Phosphorus

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Abstract

Resistivity measurements of a few-layer black phosphorus (bP) crystal in parallel magnetic fields up to 45 T are reported as a function of the angle between the in-plane field and the source-drain (S-D) axis of the device. The crystallographic directions of the bP crystal were determined by Raman spectroscopy, with the zigzag axis found within 5° of the S-D axis, and the armchair axis in the orthogonal planar direction. A transverse magneto-resistance (TMR) as well as a classically forbidden longitudinal magneto-resistance (LMR) are observed. Both are found to be strongly anisotropic and non-monotonic with increasing in-plane field. Surprisingly, the relative magnitude (in %) of the positive LMR is larger than the TMR above ~32 T. Considering the known anisotropy of bP whose zigzag and armchair effective masses differ by a factor of approximately seven, our experiment strongly suggests this LMR to be a consequence of the anisotropic Fermi surface of bP.

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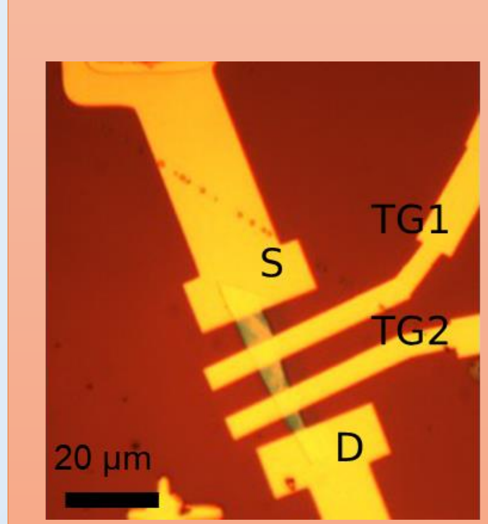
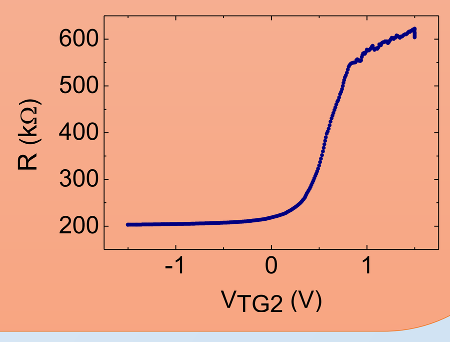
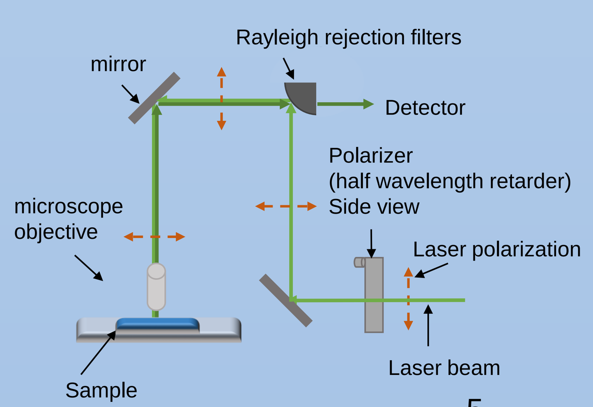
bP FET Device

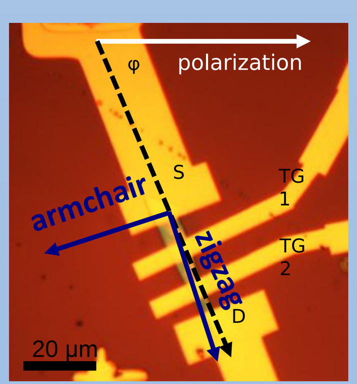


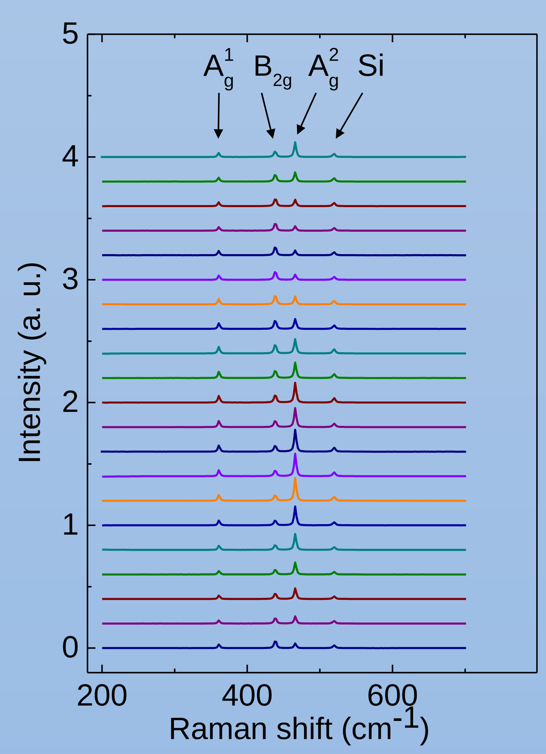
- (16±1) nm thick bP flake
- Two top gates TG1 and TG2 fabricated with a combination of PO_x and Al_2O_3 (cf. W. Dickerson et al., APL 112, (2018) 173101)
- n = 2.2 x 10^{12} cm^{-2} and μ = 83 cm^2/(Vs) at 1.5 K, 11.4 T

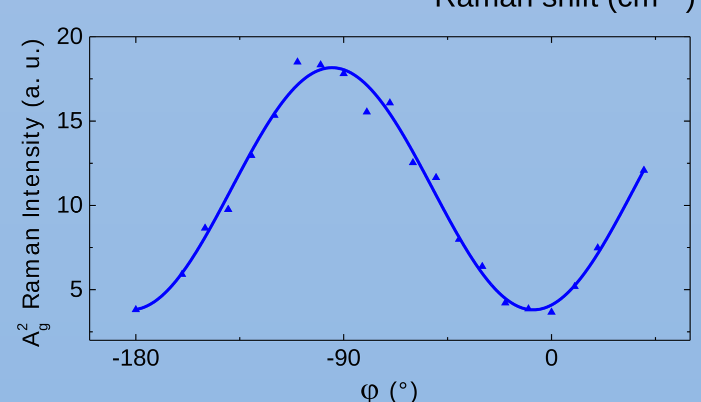


Crystal orientation: polarized Raman



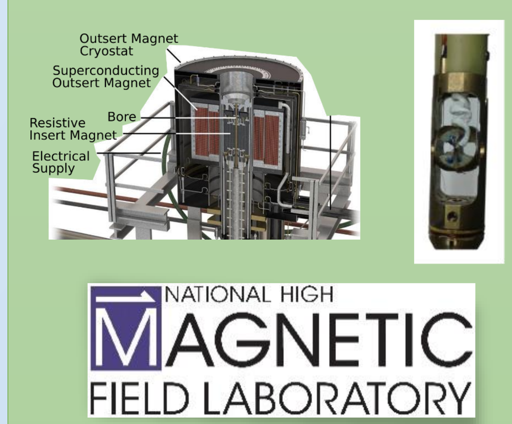


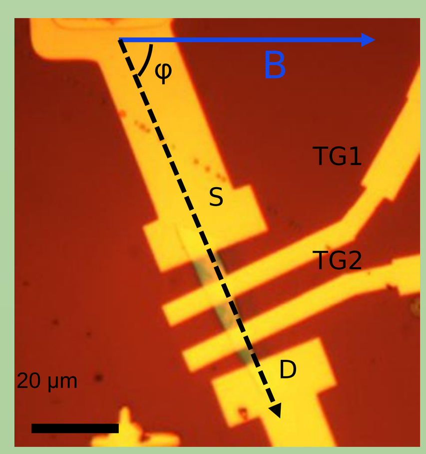




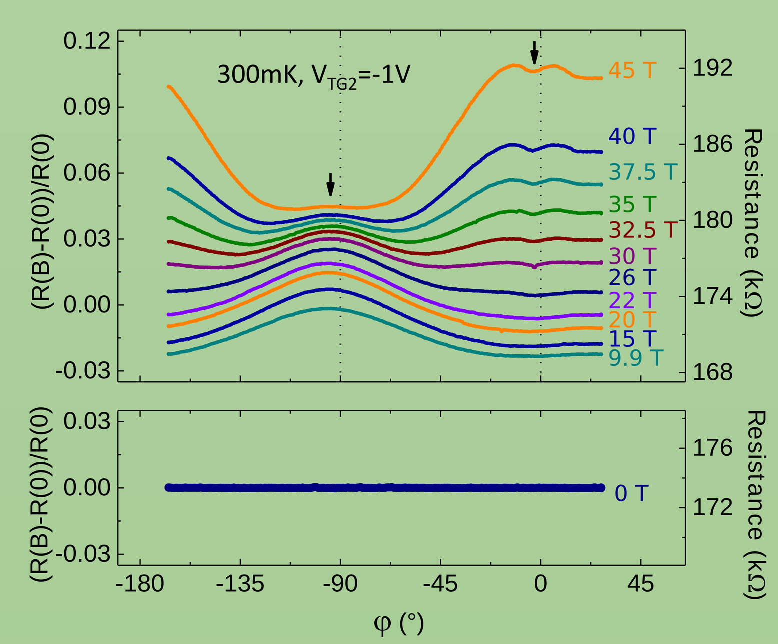
In-plane Magnetotransport

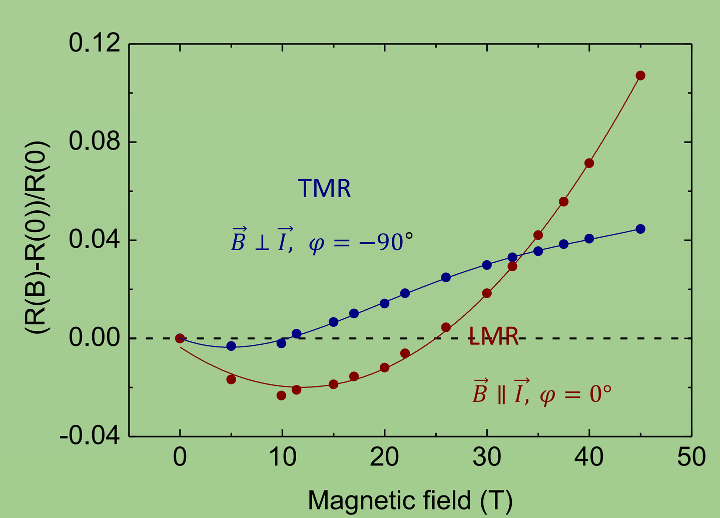
Hybrid 45 T magnet Tallahassee, USA





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



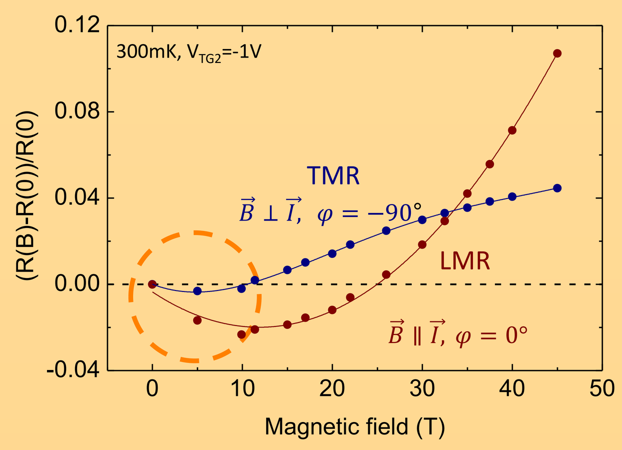


- The conventional model based on Lorentz force cannot produce longitudinal magnetoresistance LMR, since $\vec{v} \parallel \vec{B}$

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

- A longitudinal magnetoresistance has been measured in 1994 in bulk bP but never been understood [T. Strutz et al, Physica B 194 (1994) 1185].

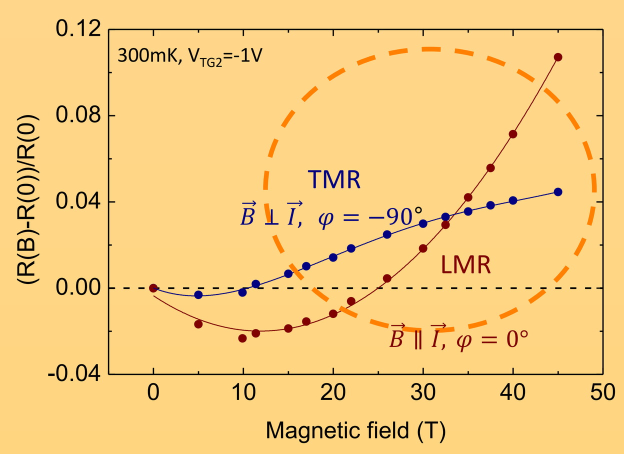
Low Field Regime



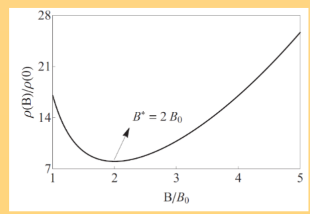
- bP has an elliptical in-plane Fermi surface
- Elastic mean free path: $l_{e,zz} = 3.2\ nm$
- Ioffe-Regel criterion: $\alpha = l_{e,zz} k_{F,zz} = 1.9$
- Close to strong localization
- Consistent with previous literature on disordered/localized bP [1]

[1] N. Iwasaki et al, Chemistry Lett. 14 (1985) 119; T.-H. Lee et al, Phys. Stat. Sol. RRL 10 (2016) 819, S. J. Choi et al, Nano Letters 16 (2016) 3969, G. Long et al Nanotechnology 29 (2018) 035204 ; N. Hemsworth et al, PRB 94 (2016) 245404.

High Field Regime



- LMR can arise in case of Fermi surface anisotropy [2]
- Its sign can be negative or positive (and it can change) for different scattering mechanisms, from short range to long range scattering [3]



- This picture still holds in a semiclassical regime [4]

[2] Pal and Maslov, PRB 81 (2010) 214438
[3] Goswami, Pixley and Das Sarma, PRB 92 (2015) 075205
[4] Son and Spivak, PRB 88 (2013) 104412

Conclusions

- In-plane magnetoresistance of a bP FET
- The observed behavior is strongly anisotropic
- Fermi surface anisotropy, with the field rotating in the plane where anisotropy is pronounced, plays a crucial role in explaining this phenomenon

F. Telesio *et al.*, arXiv:1808.00858