Strong anisotropic in-plane magnetotransport in a few-layer bP FET.

Francesca Telesio[1], Nicholas Hemsworth[2], Will Dickerson[2], Matei Petrescu[3], Vahid Tayari[2], Oulin Yu[3], David Graf[4], Manuel Serrano-Ruiz[5], Maria Caporali[5], Maurizio Peruzzini[5], Danil Bukhvalov[6], Thomas Szkopek[2], Guillaume Gervais[3] and Stefan Heun[1]

[1] *NEST, Istituto Nanoscienze–CNR and Scuola Normale Superiore, I-56127 Pisa, Italy*
[2] *Department of Electrical and Computer Engineering, McGill University, Montréal, Québec, H3A 2A7, Canada*
[3] *Department of Physics, McGill University, Montréal, Québec, 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*
[6] *Department of Chemistry, Hanyang University, 17 Haengdang-dong, Seongdong-gu, Seoul 04763, Republic of Korea*

Since its re-discovery in 2014 as van der Waals material suitable for mechanical exfoliation, black phosphorus (bP) attracted great interest, mostly due to its direct band gap that depends on the number of layer, as well as its strong in-plane anisotropy. This latter property is caused by the puckered structure of the individual bP plane forming the atomic crystal. This anisotropy has been observed in its optical, thermal, and electronic transport properties[1,2], as well as in quantum-interference effects such as weak localization[3].

Previous magnetotransport focused mainly on the Shubnikov de Haas oscillations[4] and on the quantum Hall effect[5]. Here, we report in-plane magnetoresistance measurements of a thin bP film forming a field-effect transistor. The resistivity was determined as a function of the angle between the in-plane magnetic field and the crystallographic axis of the bP flake, as determined by polarized Raman spectroscopy. The observed in-plane magnetoresistance is found to be as large as 10%, is strongly anisotropic, and it varies non-monotonically with increasing field up to 45T (at a fixed angle). The conventional theory of magnetoresistivity drastically fails to account for the behavior observed at very large fields. In this regime, the magnetoresistance exhibits clear maxima (minima) when the magnetic field is aligned along the zig-zag (armchair) axis, respectively. Taking anisotropy into account and introducing a correction for the carriers' velocity due to the Lorentz force, a model was developed that remarkably capture the essence of this anisotropic magnetoresitive effect.

1. Xia, F., Wang, H. & Jia, Y. Rediscovering black phosphorus as an anisotropic layered material for optoelectronics and electronics. *Nat. Commun.* **5,** 4458 (2014).
2. Luo, Z. *et al.* Anisotropic in-plane thermal conductivity observed in few-layer black phosphorus. *Nat. Commun.* **6,** 8572 (2015).

3. Hemsworth, N. *et al.* Dephasing in strongly anisotropic black phosphorus. *Phys. Rev. B* **94,** 245404 (2016).
4. Tayari, V. *et al.* Two-Dimensional Magnetotransport in a Black Phosphorus Naked Quantum Well. *Nat. Commun.* **6,** 1–7 (2014).
5. Li, L. L. *et al.* Quantum Hall effect in black phosphorus two-dimensional electron system. *Nat. Nanotechnol.* 6–10 (2016). doi:10.1038/nnano.2016.42

e-mail addresses:

Francesca Telesio: francesca.telesio@nano.cnr.it
Nicholas Hemsworth: nicholas.hemsworth@gmail.com
Will Dickerson: william.dickerson@mail.mcgill.ca
Matei Petrescu: matei.petrescu@mail.mcgill.ca
Vahid Tayari: vahid.tayari@gmail.com
Oulin Yu: yu.oulin@gmail.com
David Graf: graf@magnet.fsu.edu
Manuel Serrano-Ruiz: mserrano@iccom.cnr.it
Maria Caporali: maria.caporali@gmail.com
Maurizio Peruzzini: maurizio.peruzzini@gmail.com
Danil Bukhvalov: danil@hanyang.ac.kr
Thomas Szkopek: thomas.szkopek@mcgill.ca
Guillaume Gervais: gervais@physics.mcgill.ca
Stefan Heun: stefan.heun@nano.cnr.it