Two-Dimensional Transport in a Black Phosphorus Naked Quantum Well

Thomas SZKOPEK[1], Vahid TAYARI[1], Nicholas HEMSWORTH[1], Ibrahim FAKIH[1], Alexandre FAVRON[2], Etienne GAUFRÈS[2], Guillaume GERVAIS[1], Richard MARTEL[2]

[1] *McGill University, 845 Rue Sherbrooke Ouest, Montréal, Canada*
[2] *Université de Montréal, 2900 Boulevard Edouard-Montpetit, Montréal, Canada*
thomas.szkopek@mcgill.ca

Abstract Black phosphorus (bP) is the second known elemental allotrope with a layered crystal structure that can be mechanically exfoliated down to atomic layer thickness. We have fabricated bP naked quantum wells in a back-gated field effect transistor (FET) geometry with bP thicknesses ranging from 6±1 nm to 47±1 nm. The deleterious effects of photo-oxidation [1] were mitigated by using bP layers thicker than a few atomic layers, by encapsulating the bP quantum wells with a polymer, and by minimizing exposure to oxygen, water and visible light. We have measured the electronic transport properties of bP FETs over the temperature range of 300 mK to 300 K. Zero-field transport measurements reveal ambipolar transport, field effect mobilities of up to 600 cm^2/Vs, and on/off current ratios exceeding 10^5. Shubnikov-de Haas (SdH) oscillations were observed in a 47±1 nm thick bp FET at 300 mK and magnetic fields of up to 35 T. Landau-Kosevich analysis of the SdH oscillations indicates the presence of a 2-D hole gas with Schrödinger fermion character in an accumulation layer at the bP surface. A simple Schrödinger-Poisson analysis predicts accumulation of holes in a single 2-D sub-band at 300 mK over the range of applied electric fields used in experiment.
Our work [2] demonstrates that 2-D electronic structure and 2-D atomic structure are independent. 2-D carrier confinement can be achieved in layered semiconducting materials without necessarily approaching atomic layer thickness, advantageous for materials that become increasingly reactive in the few-layer limit such as bP. Independent studies of bP on exfoliated hexagonal boron nitride (hBN) [3], and bP encapsulated within exfoliated hBN layers [4, 5] have reported similar observations of 2D magnetotransport.

References

[1] A. Favron *et al.*, Nat. Mater. doi:10.1038/nmat4299 (2015).
[2] V. Tayari *et al.*, Nat. Commun. **6**, 7702 (2015).
[3] L. Li *et al.*, Nat. Nanotechnol. doi:10.1038/nnano.2015.91 (2015).
[4] N. Gillgren *et al.*, 2D Materials **2**, 011001 (2015).
[5] X. Chen et al., Nat. Commun. **6**, 7315 (2015).

Figures

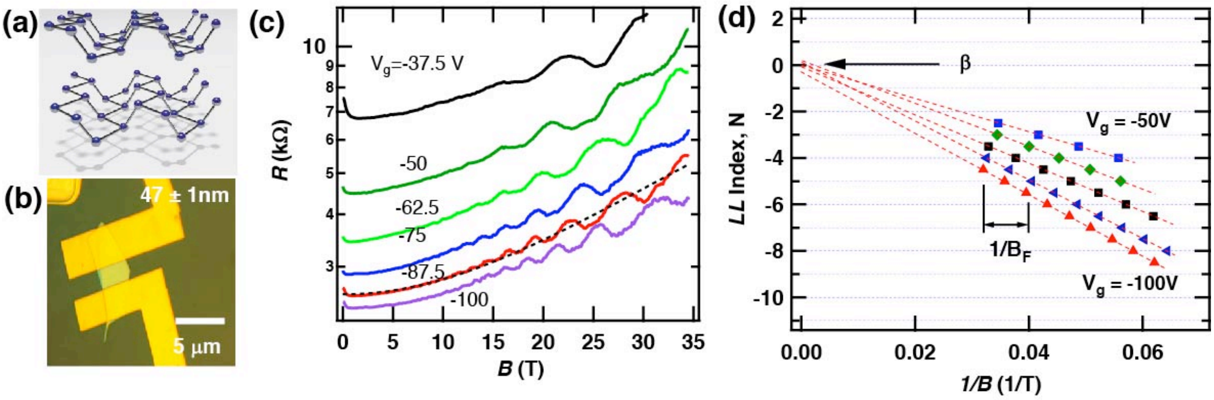

Figure: (a) Puckered honeycomb layers of black phosphorus (bP). (b) Optical image of encapsulated bP field effect transistor, with a thickness of 47±1 nm determined by atomic force microscopy. (c) Two-point resistance *R* in logarithmic scale versus applied magnetic field *B*, at 300 mK with the applied back-gate voltage V_g in the hole conduction regime indicated. (d) Landau fan diagram of orbital index versus 1/*B* determined by Landau-Kosevich analysis of SdH oscillations in (c). A 2D hole gas with Schrödinger-Fermion character (Berry phase β = 0) is found.