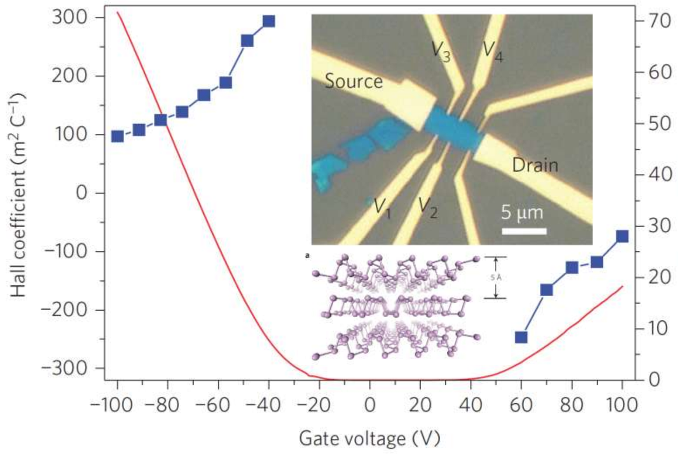
4. Properties of 2D Semiconductors
Part 2

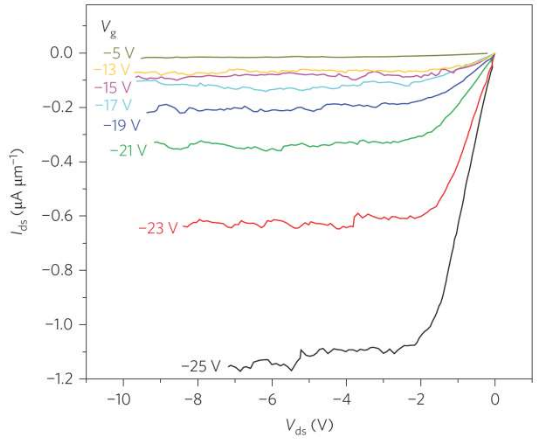
서울대학교
SEOUL NATIONAL UNIVERSITY

Properties of Black Phosphorous

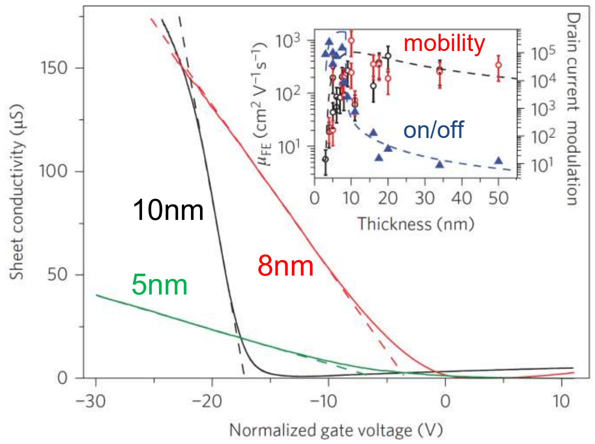
1st paper by Fudan

Electrical Transport

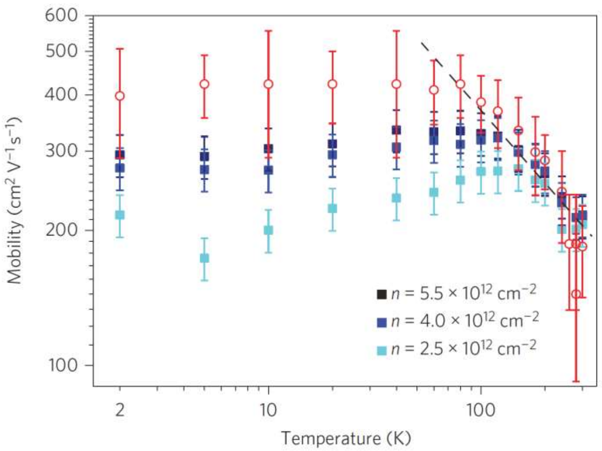




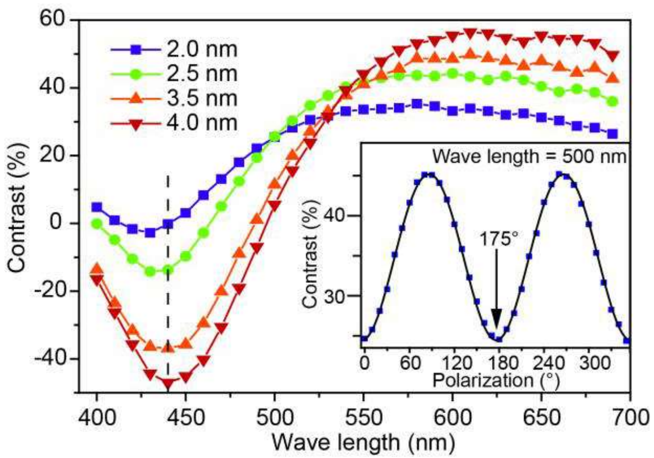
Thickness-dependence of mobility



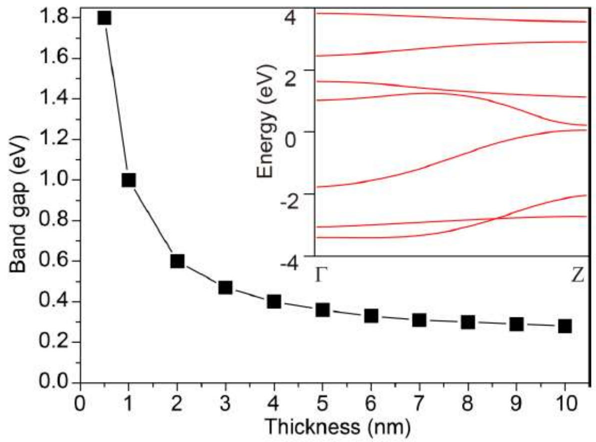
Temperature-dependence of mobility



Anisotropy in optical contrast



Thickness-dependent bandgap



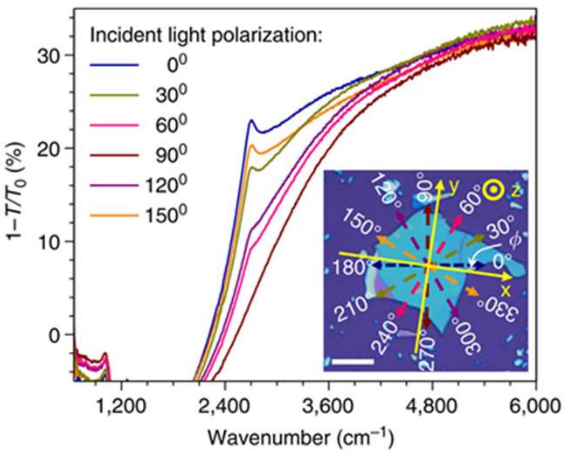
L. Li et al. Nature Nanotechnol. (2014)

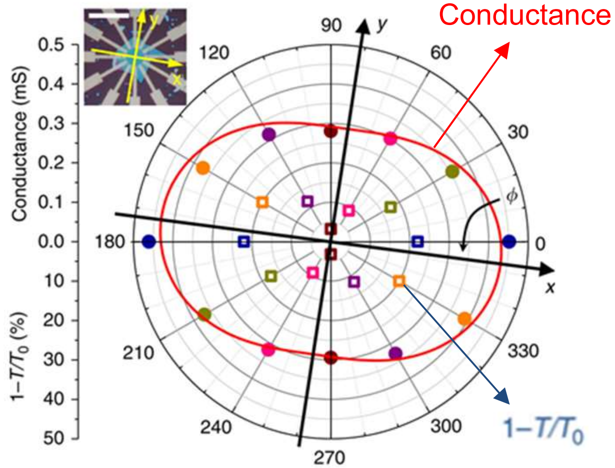
Received 9/12/2013 and published 3/2/2014

Properties of Black Phosphorous

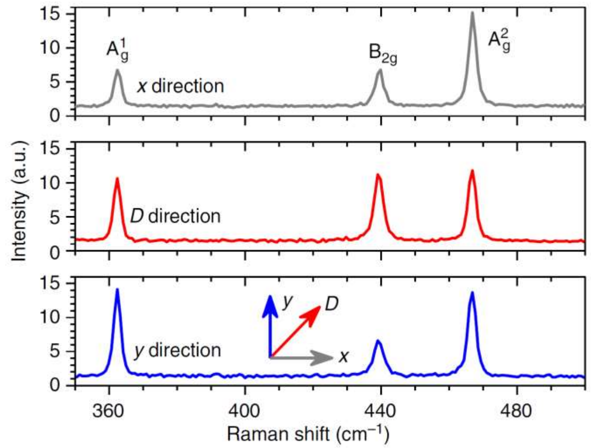
2^{nd} paper by Yale

Polarization-resolved extinction spectra

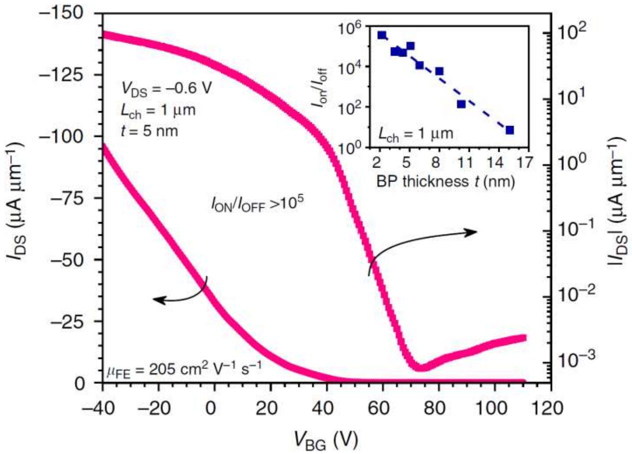




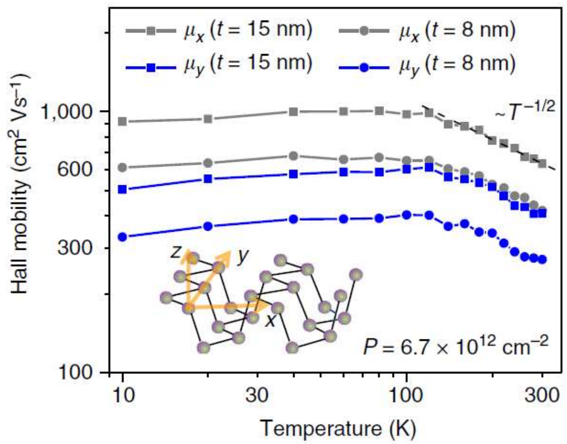
Polarized laser Raman spectroscopy



Electrical Transport



Temperature- and direction-dependence of mobility

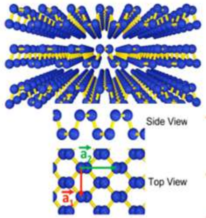


F. Xia et al. Nature Commun. (2014)

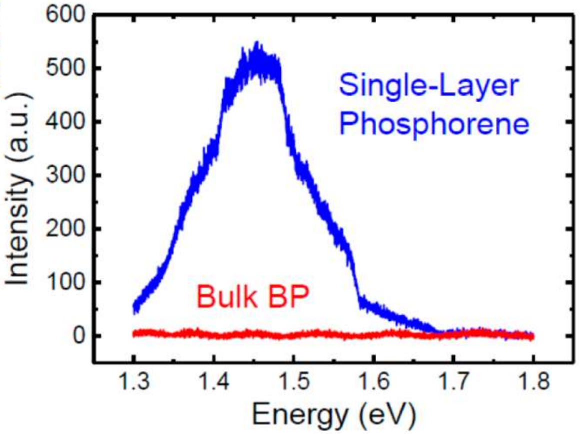
Received 2/21/2014 and published 7/21/2014

Properties of Black Phosphorous

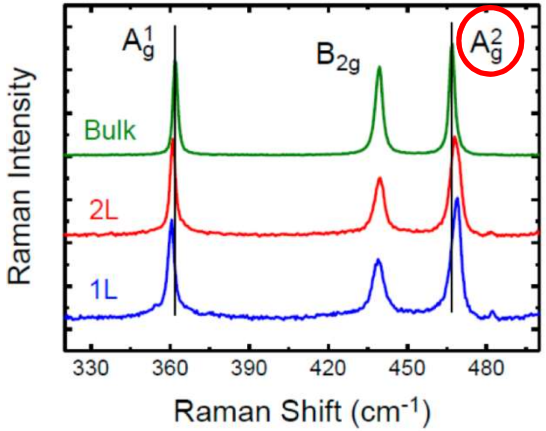
3rd paper by Perdue



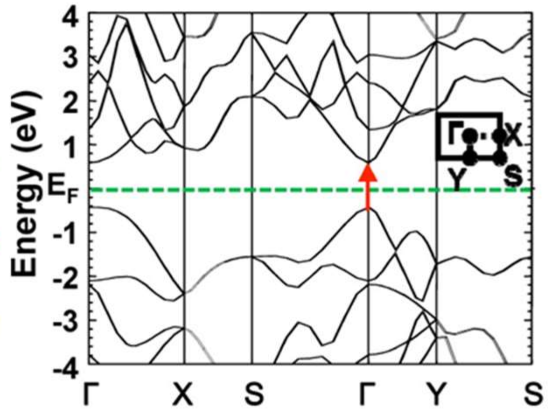
Photoluminescence spectra



Raman spectroscopy

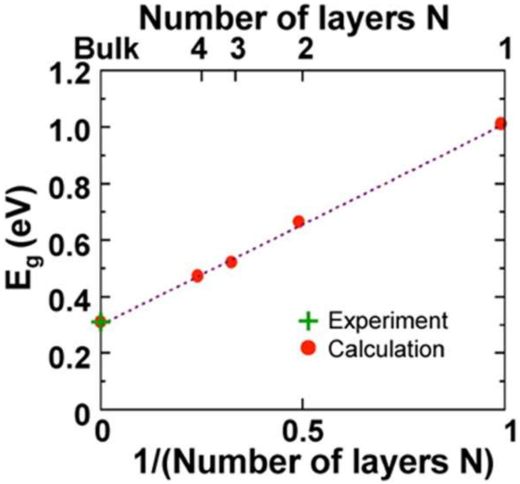


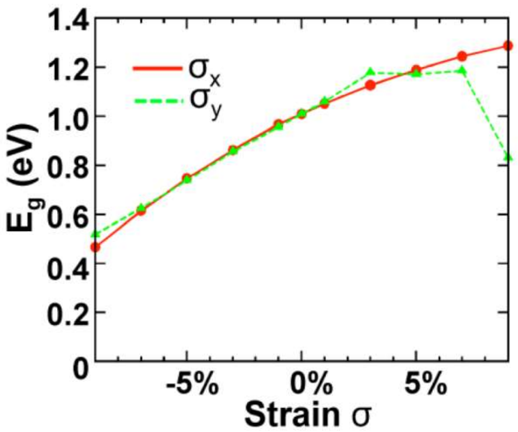
Band structure

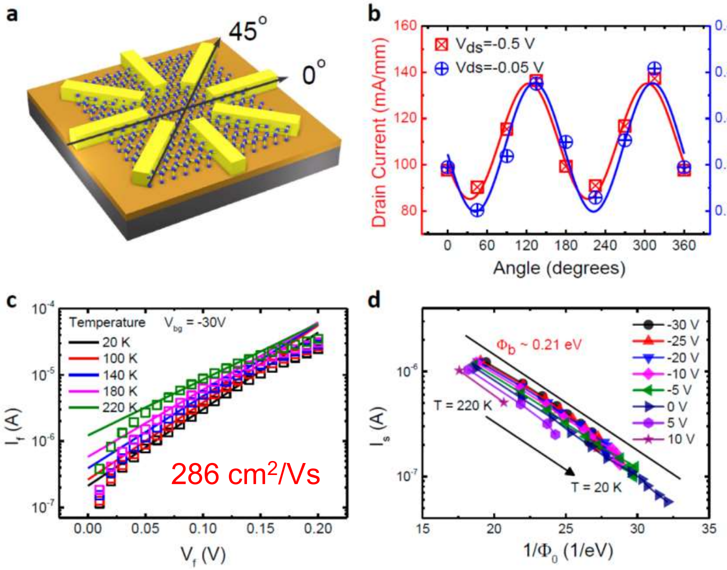


Direct band gap at all thicknesses

Thickness- and strain-dependence of bandgap





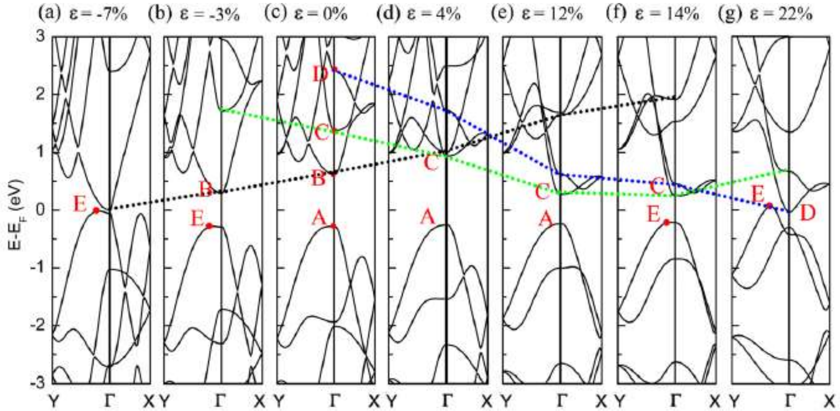


From 0.3 eV for bulk to 1.0 eV for monolayer (Simulated)
From 0.5 eV for zero strain to 1.2 eV for over 5% strain (Simulated)

Received 3/2/2014 and published 3/17/2014 *H. Liu et al. ACS Nano (2014)*

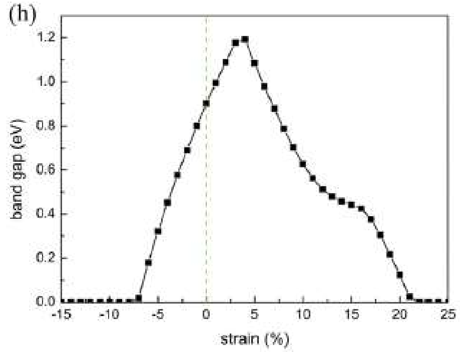
Strain-Induced Bandgap Change in Black Phosphorous

Isotropic strain

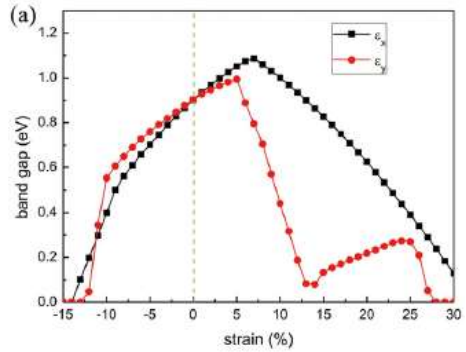


direct → indirect

Isotropic strain



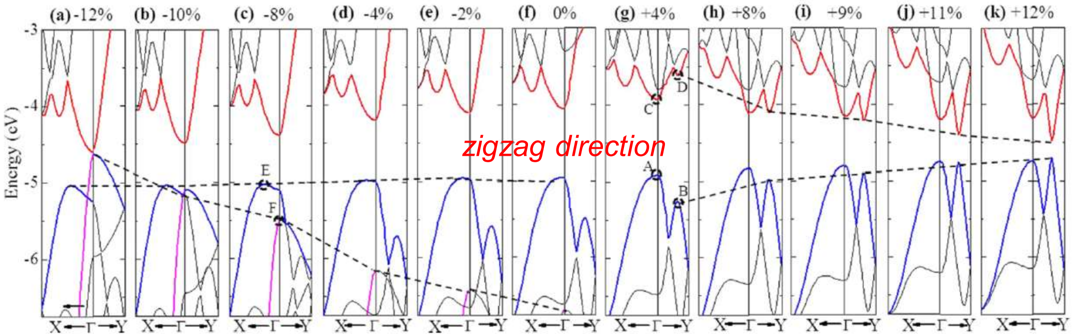
Uniaxial strain

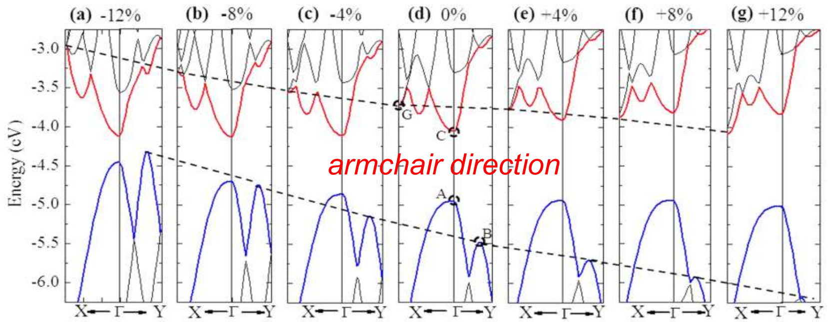


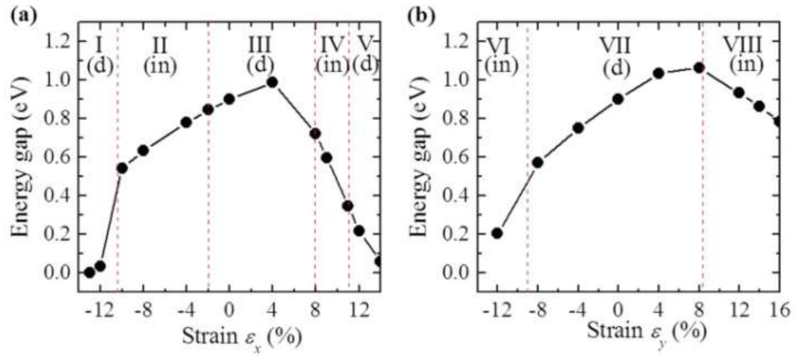
semiconductor → metal change

T. Hu et al. Nanotechnology (2014)

Uniaxial strain(monolayer)



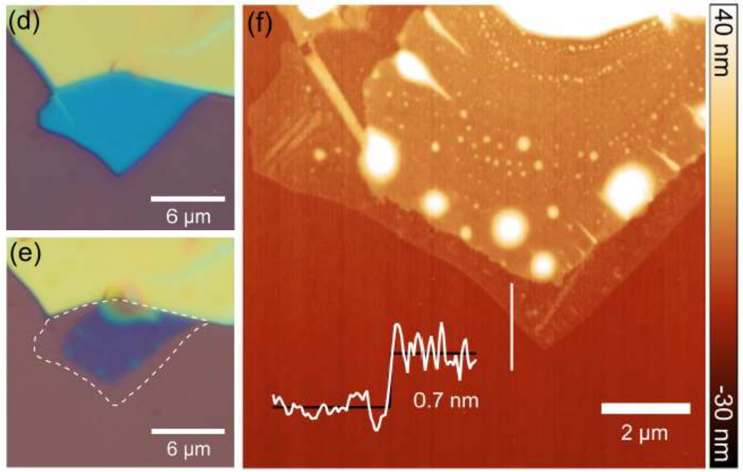




X. Peng et al. Phys. Rev. B (2014)

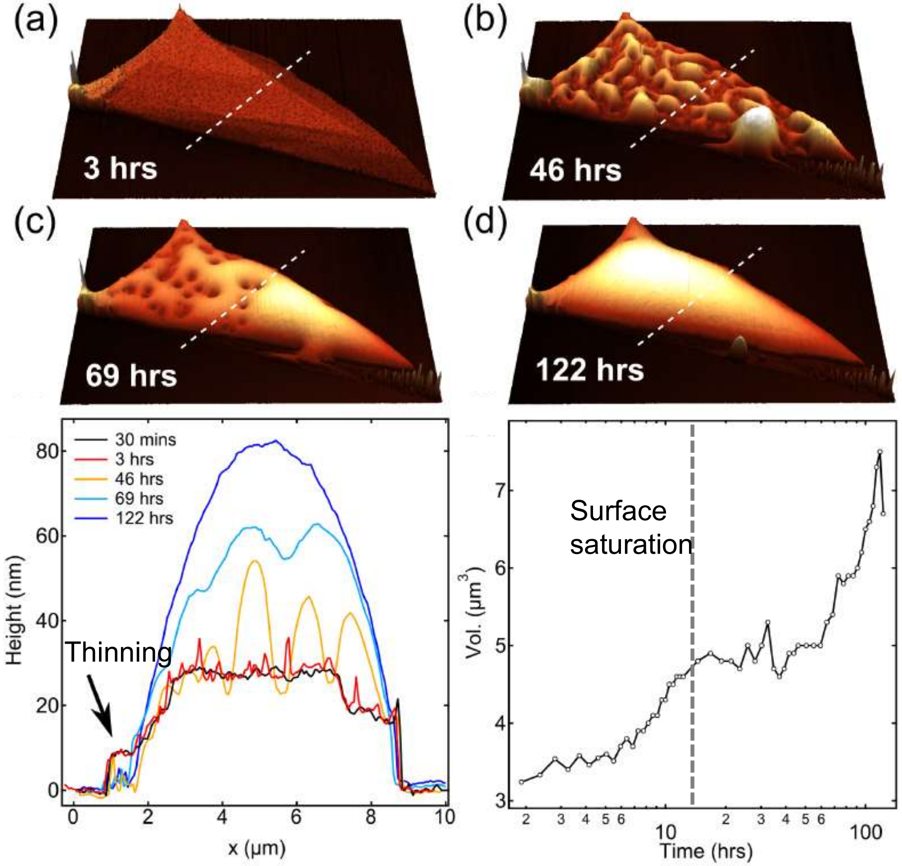
Stability of Black Phosphorous

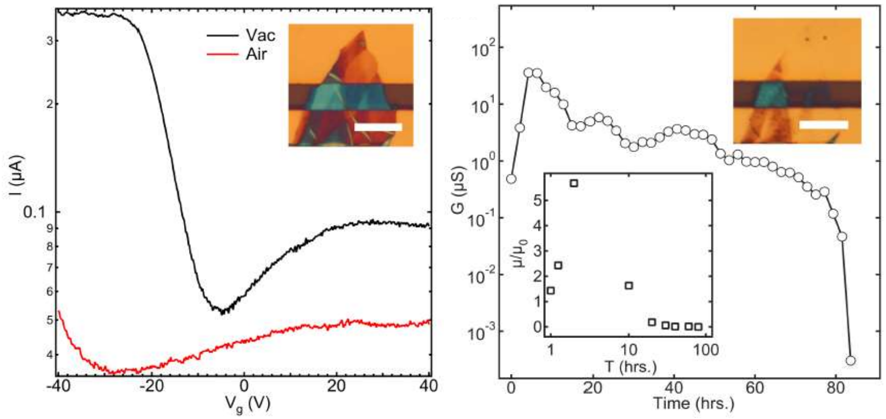
*The out-of-plane dipole moment makes black phosphorous highly **hydrophilic**.*



Fast adsorption of water on thinner flake
Layer-by-layer thinning
Transformation of edges to single layer
Etching by reaction with water or oxygen

Adsorption of water

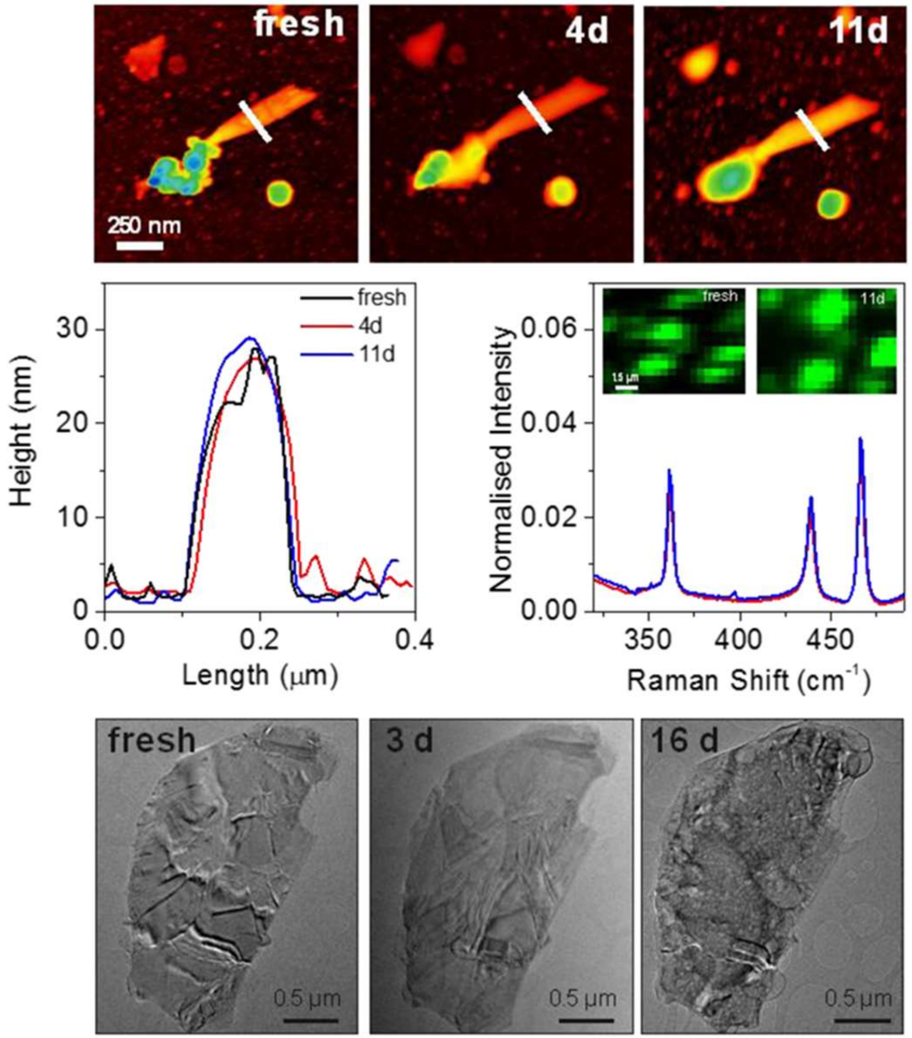


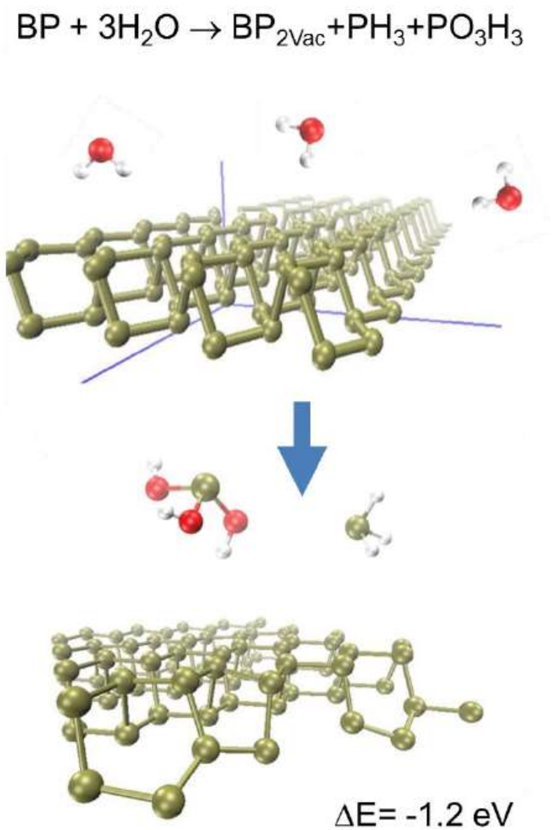


Continuous degradation and final breakdown

J. O. Island et al. 2D Materials (2015)

Stability of Black Phosphorous

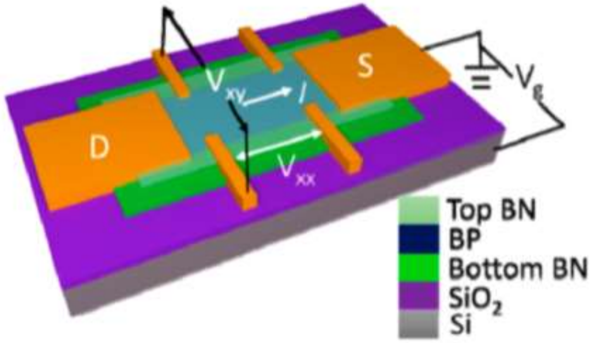




Degradation by reaction with water molecules only at the nanosheet edge, leading to the removal of phosphorus atoms and the formation of phosphine and phosphorous acid.

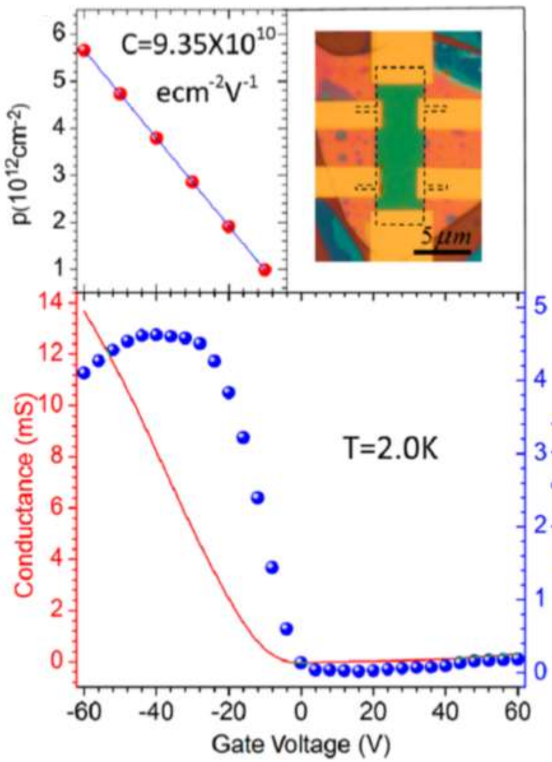
D. Hanlon et al. arXiv (2015)

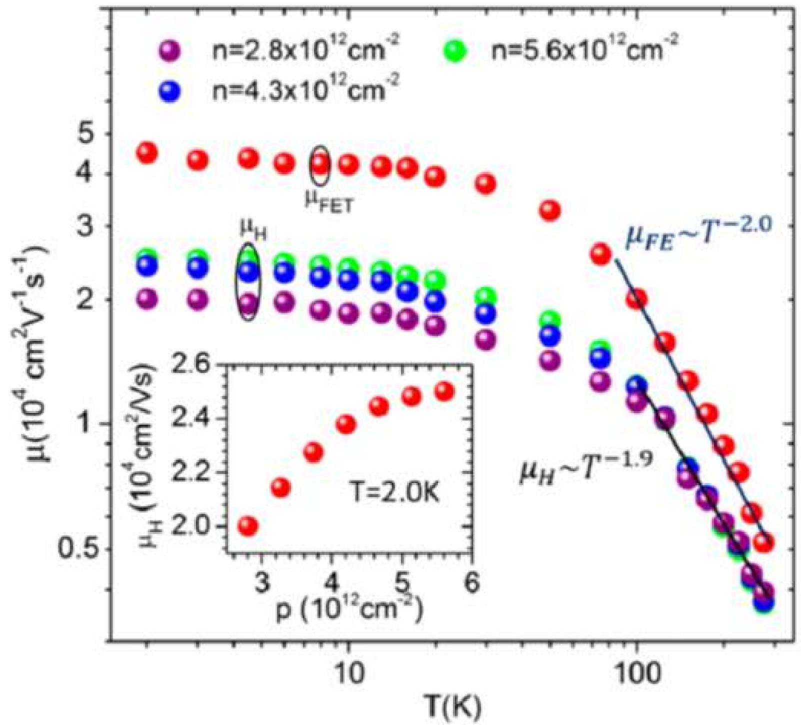
Ultrahigh carrier mobility in hBN encapsulated BP



hBN encapsulated BP FET

In vacuum and RT,
- Hole mobility of 5,200 cm^2 / Vs
- Field-effect mobility of 45,000 cm^2 / Vs

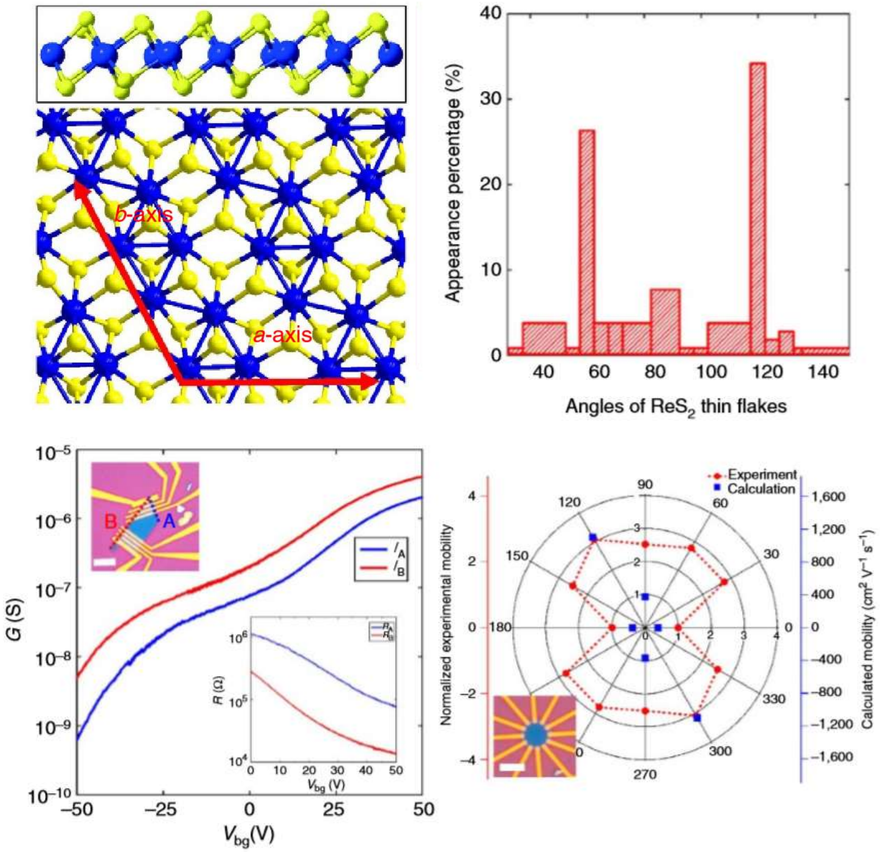




Long, G. et al. Nano Lett. (2016)

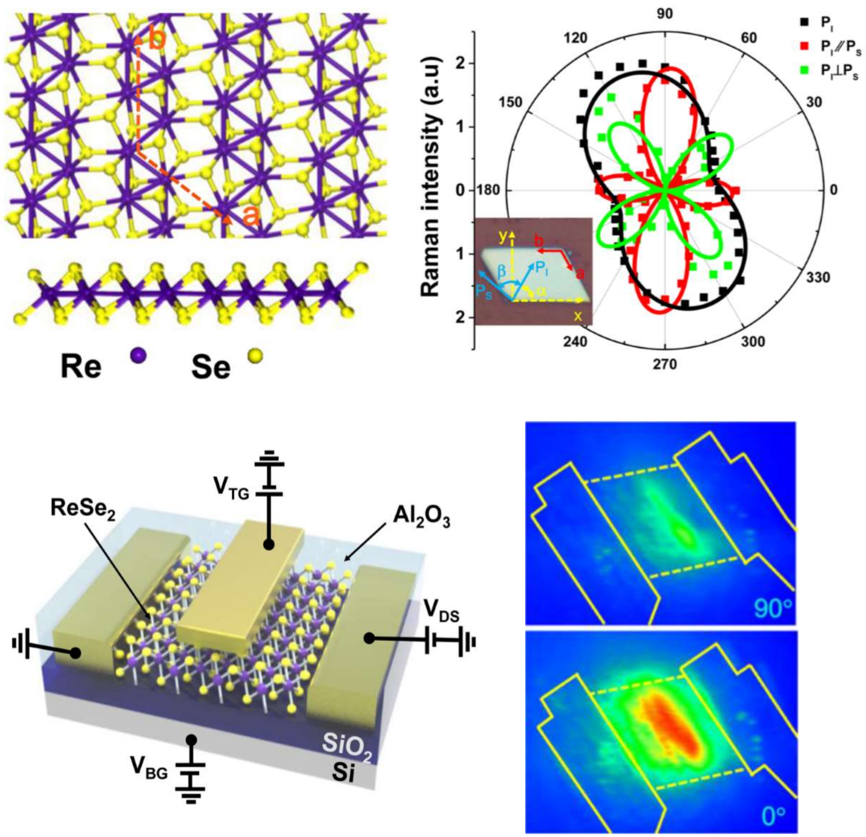
Anisotropic Two-dimensional Materials

Electrical anisotropy of ReS_2



Liu, E. et al. Nat. Commun. (2015)

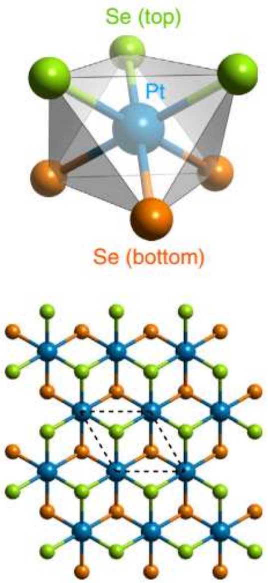
Polarization-sensitive $ReSe_2$ photodetectors

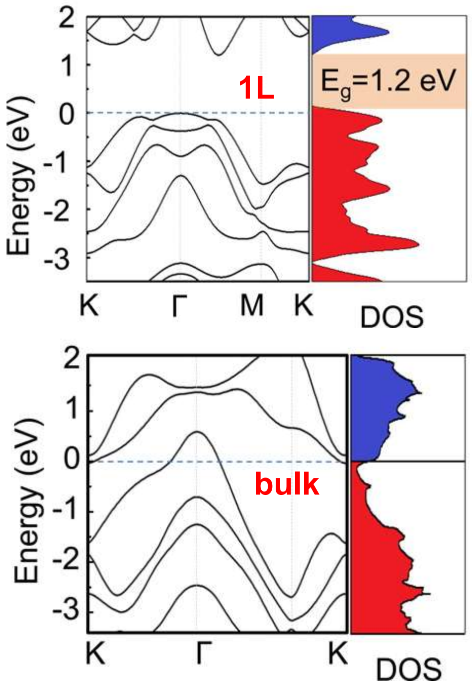


Zhang, E. et al. ACS Nano (2016)

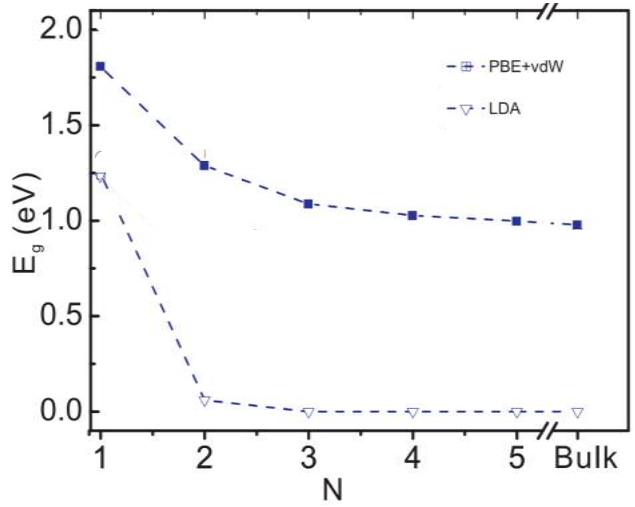
Photocurrent is generated with 0° polarized light while there is no photocurrent with 90° polarized light

Semiconductor-to-metal Transition of $PtSe_2$

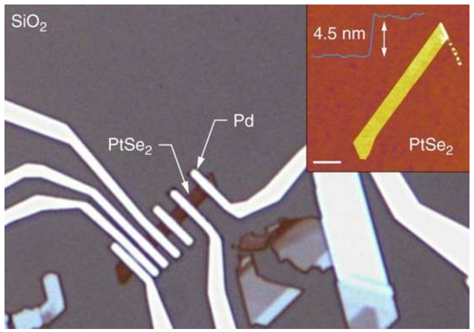


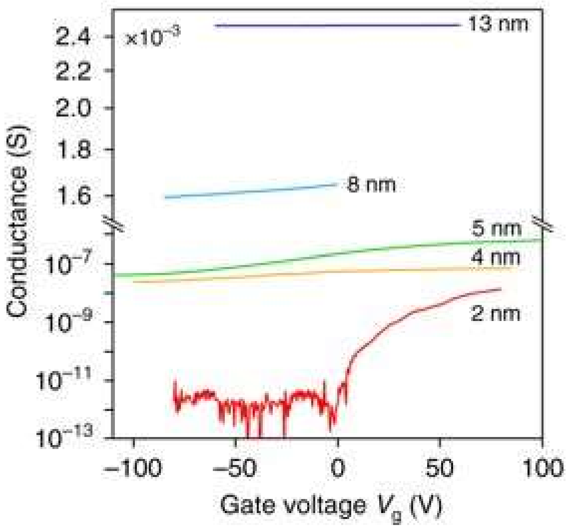


Nano Lett. (2015)



J Mater. Chem. C (2016)



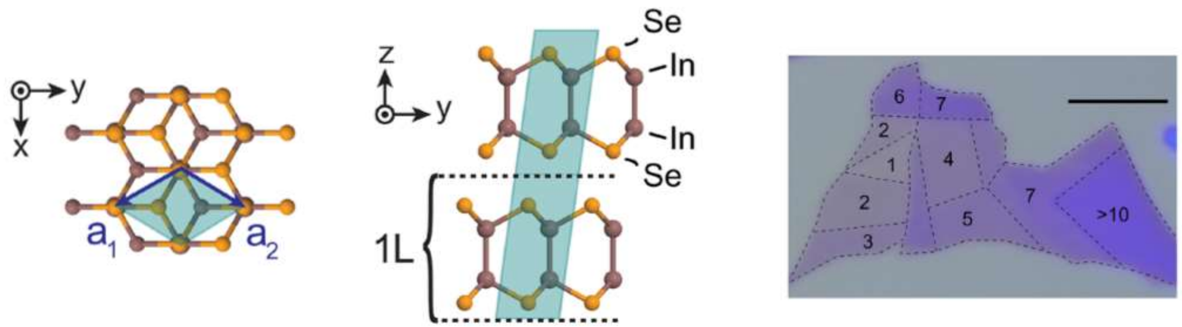


Nature Commun. (2018)

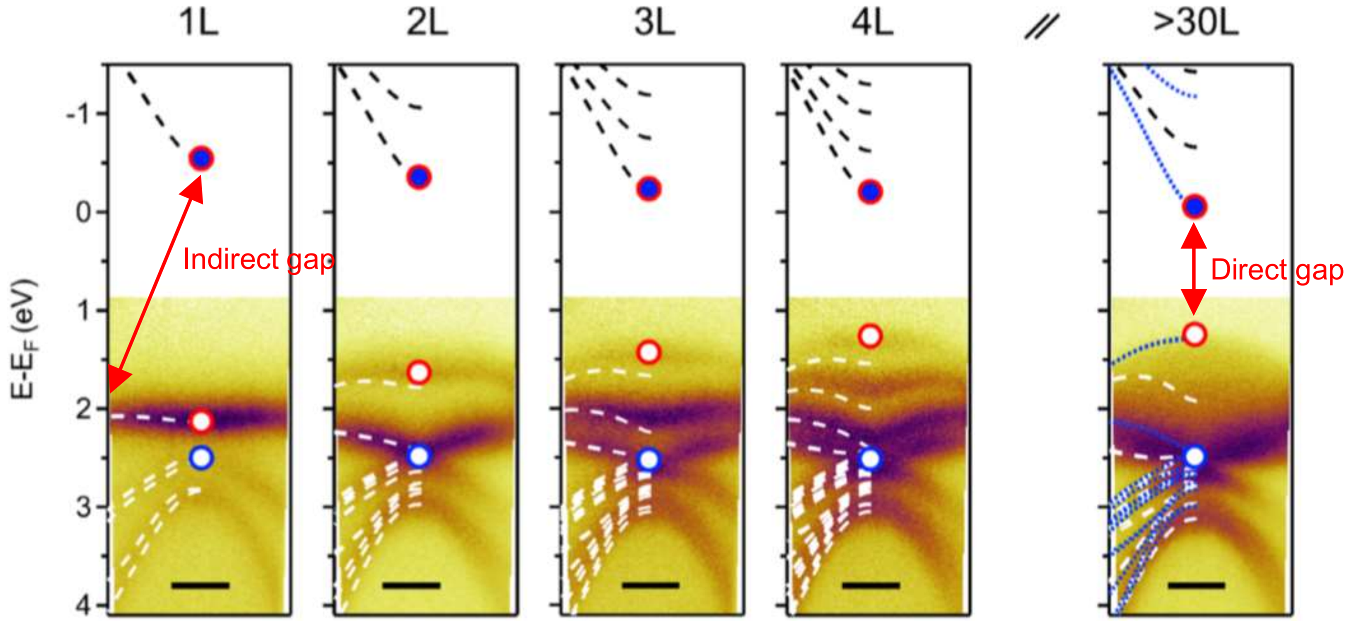
- Theoretically, semiconductor of 1.2 eV for monolayer and metallic for thicker layer
- Experimentally, 2nm-thick $PtSe_2$ shows n-type behavior.

Indirect to Direct Bandgap Transition in InSe

Atomic structure of InSe



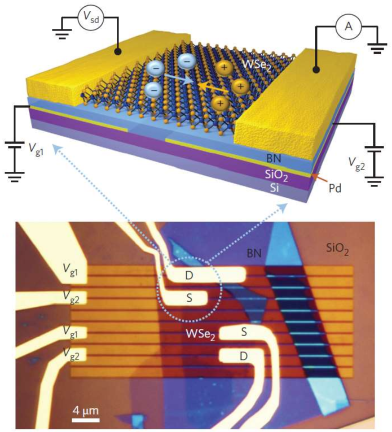
Angle-resolved photoemission spectroscopy (ARPES)

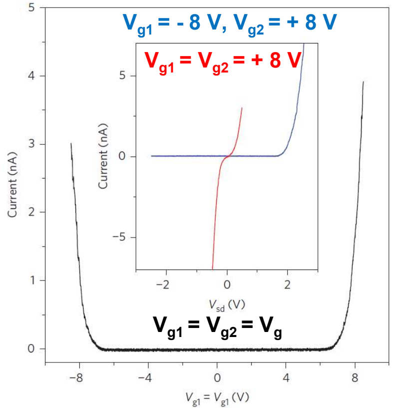


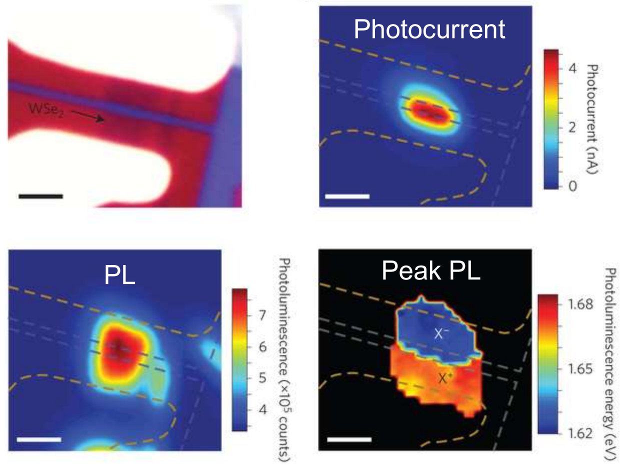
Hamer, M. J. et al. ACS Nano (2019)

Electrical Tunability of 2D Semiconductors

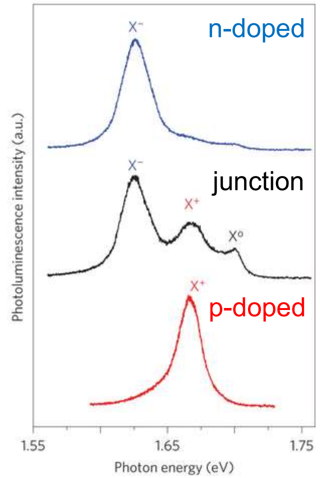
WSe_2 p–n junction devices with split back-gates

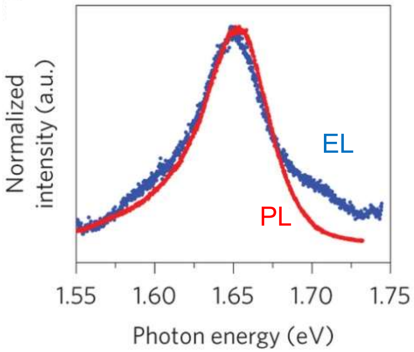


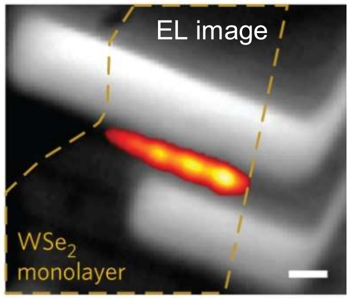




Photoluminescence

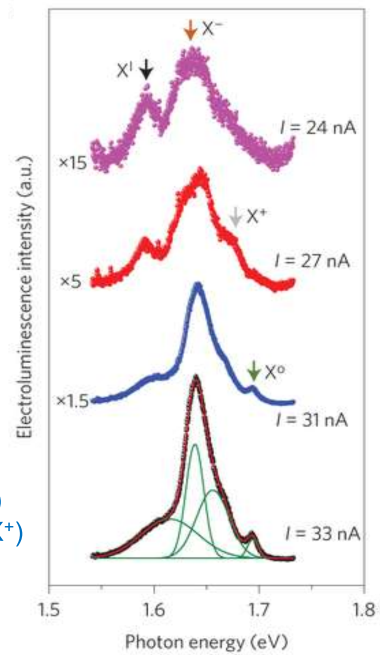




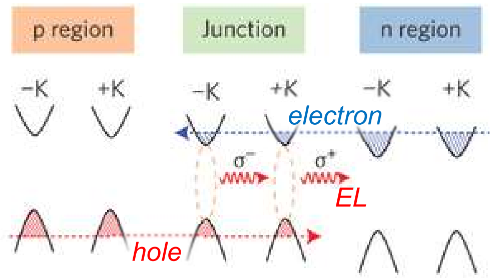


impurity-bound exciton (X^I)
charged excitons (X^- and X^+)
neutral exciton (X^o)

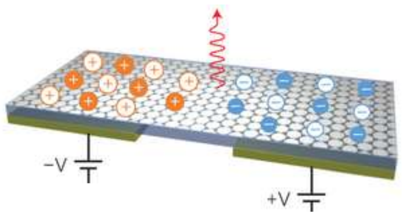
Electroluminescence



EL generation from valley excitons



right (σ^+) and left (σ^-) circular polarization

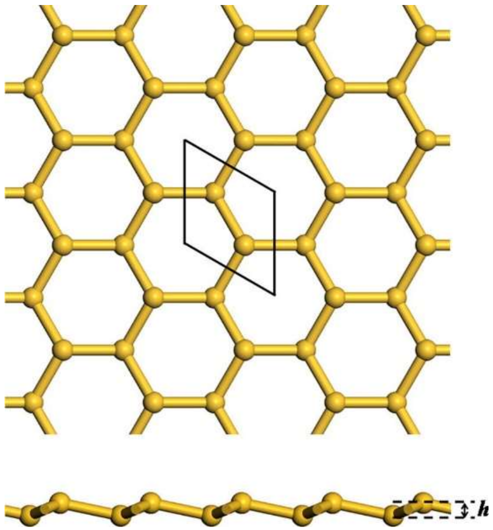


Filled and empty circles indicate carriers in the +K and -K valleys

J. S. Ross et al. Nature Nanotechnol. (2014) & B. W. H. Baugher et al. Nature Nanotechnol. (2014) & A. Pospischil et al. Nature Nanotechnol. (2014)

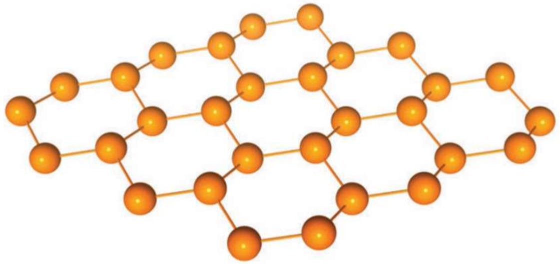
Group IV 2D Materials

Silicene (Si)



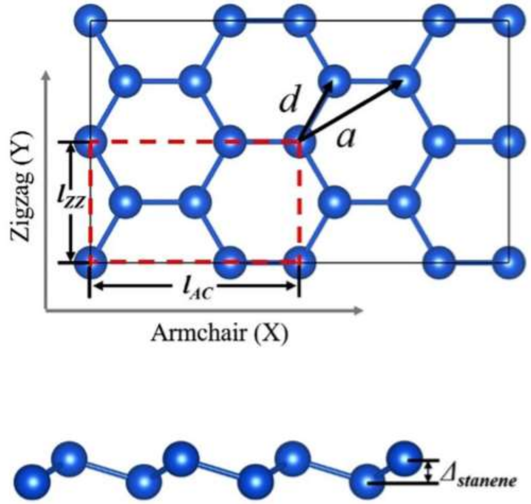
Zhao, J. et al. Pro. in Mat. Sci. (2016)

Germanene (Ge)



Wei, W. et al. Phys. Chem. Chem. Phys. (2013)

Stanene (Sn)



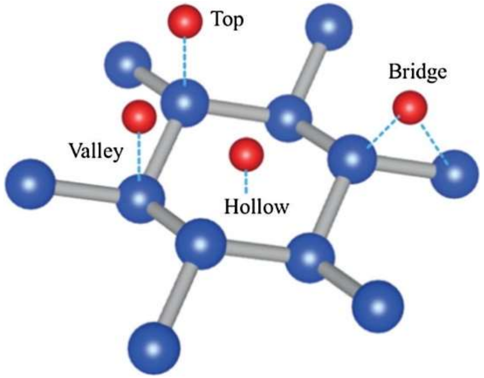
Lu, P. et al. Sci. Rep. (2017)

- Graphene-like honeycomb structure materials
- Linear dispersion at Dirac point
- High electron mobility
- 2-3% of light absorption
- Strong spin-orbit coupling

  → Better tunability of the band gap

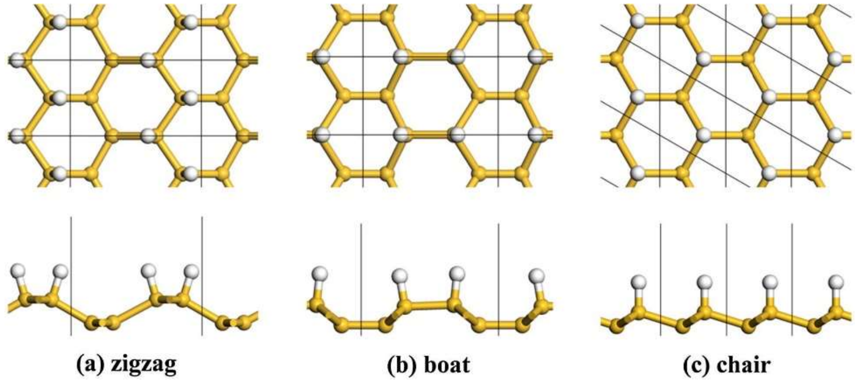
Functionalization of Silicene

Possible adsorption sites of silicene



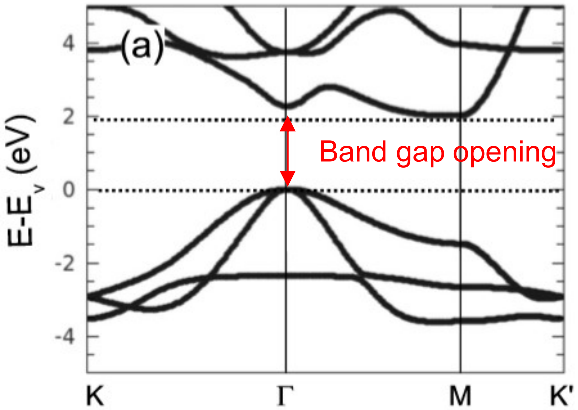
Sahin, H. Phys. Rev. B (2013)

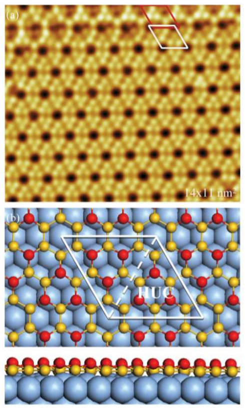
Atomic structure of functionalized silicene



Zhao, J. et al. Pro. in Mat. Sci. (2016)

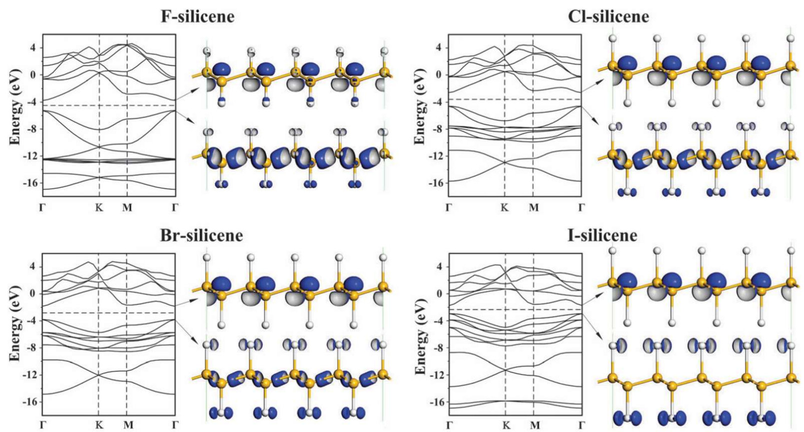
Hydrogenation





Houssa, M. et al. Appl. Phys. Lett. (2011) *Qiu, J. et al. PRL (2015)*

Halogenation

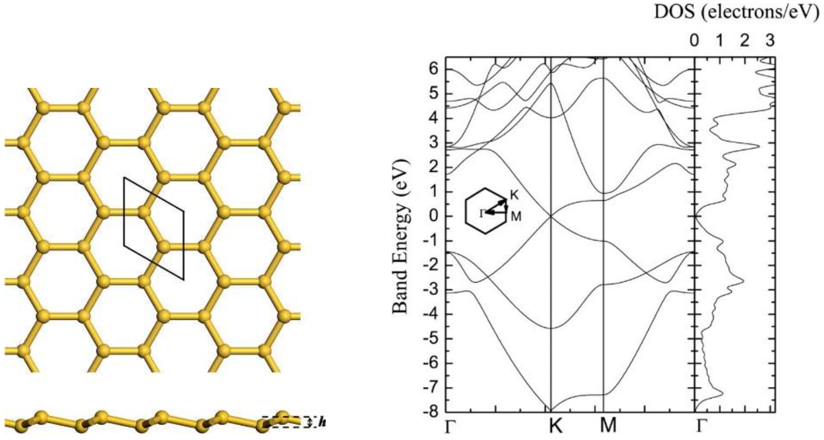


Gao, N. et al. Phys. Chem. Chem. Phys. (2011)

Band gap of silicene can be opened by functionalization, converted sp^2 hybridized silicon into sp^3

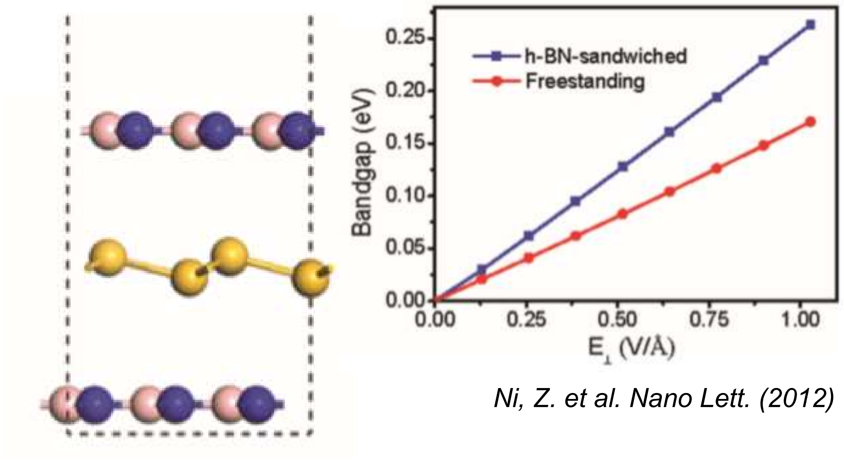
Electrical Properties of Silicene

Band structure of silicene



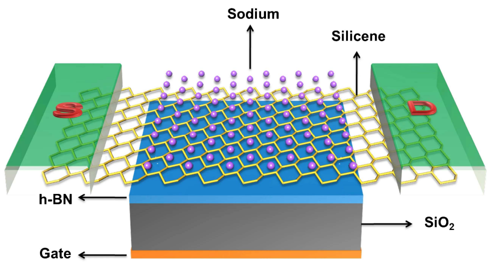
Zhao, J. et al. Pro. in Mat. Sci. (2016)

Band gap tuning in hBN-sandwiched silicene

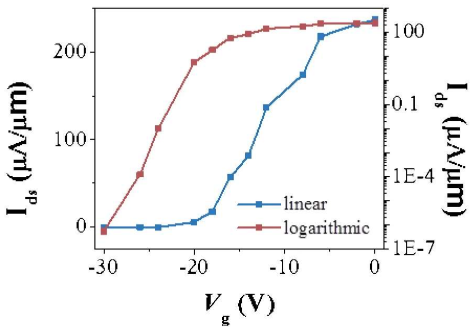


Ni, Z. et al. Nano Lett. (2012)

Sodium treated silicene FET

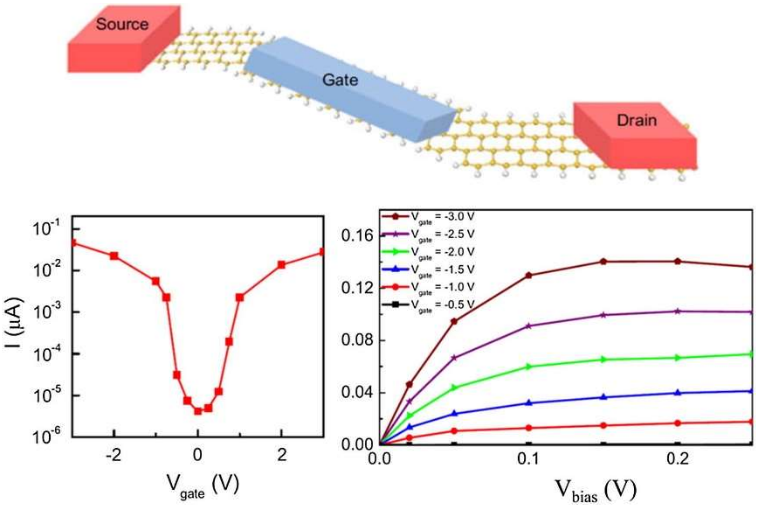


n-type semiconducting behavior



Quhe, R. et al. Sci. Rep. (2012)

Hydrogenated silicene nanoribbon FET



Li, H. Eur. Phys. J. B (2012)