Quantum Hall Effect in Few-layer Atomic Membranes

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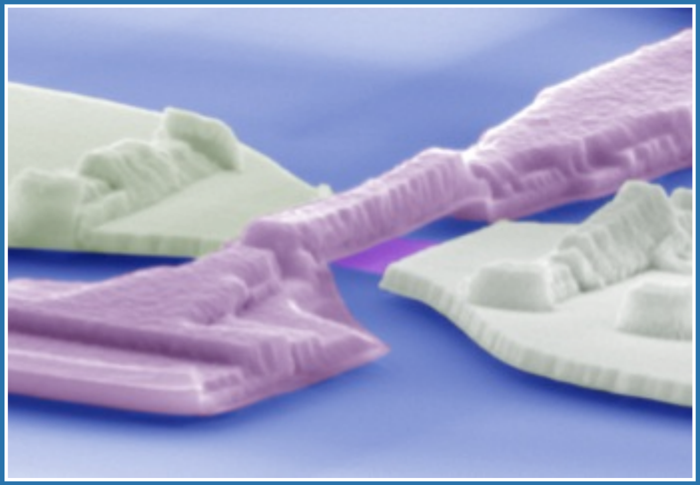


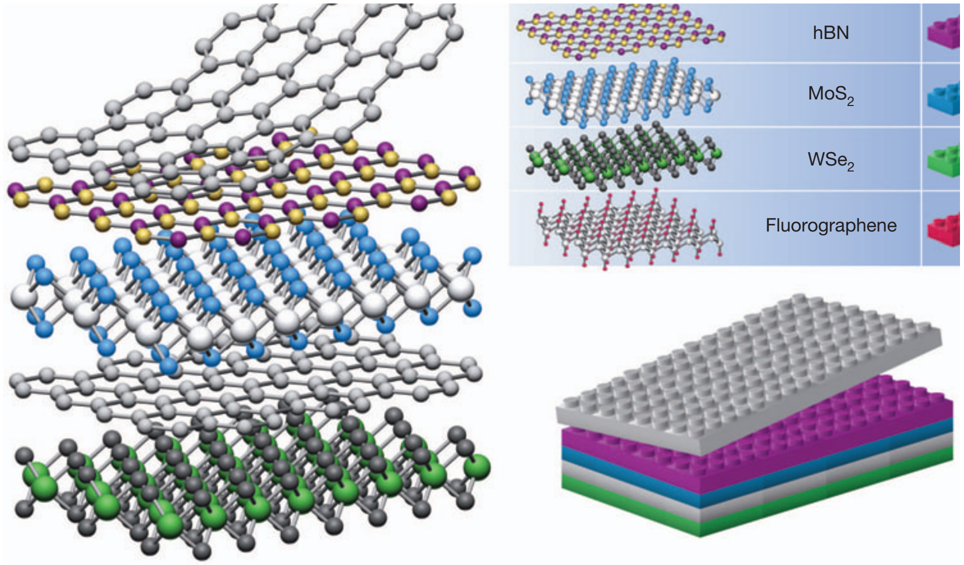
Outline

- Symmetry-broken Ground State in Few Layer Graphene

- Transport Properties of Ionic Liquid-Gated Suspended MoS_2 Transistors

- Quantum oscillations in Few-layer Phosphorene

2D Materials and Heterostructures



Geim, Nature 2013.

- Conductors, e.g. graphene, few-layer graphene
- Semiconductors, e.g MoS_2, WS_2,
- Superconductors, Nb_2Se_3
- Insulators, e.g. hBN
- Charge density waves, e.g. NbSe
- Ferromagnets, e.g. VSe_2

What to ask a material scientist/experimentalist

What to ask a material scientist/experimentalist

High Mobility allows exploration of

- **Better electronic devices and transistors**
- **Novel phenomena not obscured by disorder**
  - **integer and fractional quantum Hall effect**
  - **magnetic focusing**
  - **electron optics**
  - **electron correlation**
  - **spontaneous symmetry breaking**
  - **….**
- **ultimate possibilities**
  - **set the stage for technological innovations and revolutions**

Usual Suspects of Mobility Bottleneck

- Lattice defects/substitutions/vacancies
- Phonons
  - intrinsic
  - surface phonons from substrates
- Impurities
  - intrinsic
  - charged impurities/dangling bonds from substrates
- Ripples and corrugations
  - intrinsic
  - substrates

Schottky barriers (for semiconducting 2D materials)

→ substrate engineering
- elimination (suspended samples) — Andrei group, Kim group
- atomically flat, no dangling bonds → hexagonal BN — Columbia group, Nat. Nanotechnol. 2012

There is still life in graphene….

- Extremely simple and elegant system and Hamiltonian

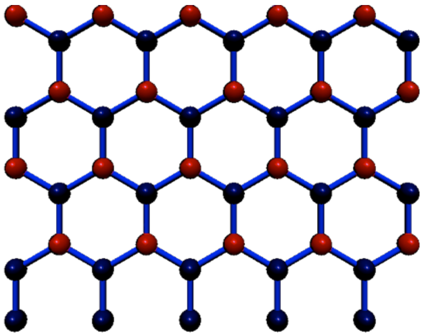
- Rich physics
  - massless or massive Dirac fermions
  - possible phases: layer antiferromagnet, ferromagnet, unconventional superconductivity, quantum spin Hall…

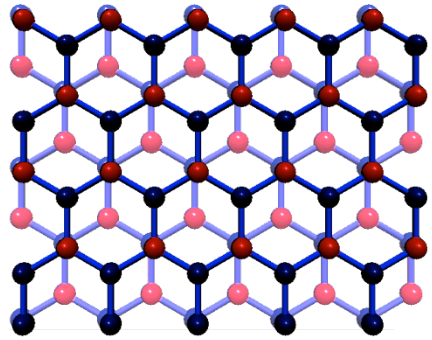
- Strong interactions in few-layer graphene with competing symmetries (layer, valley, spin, orbital…)

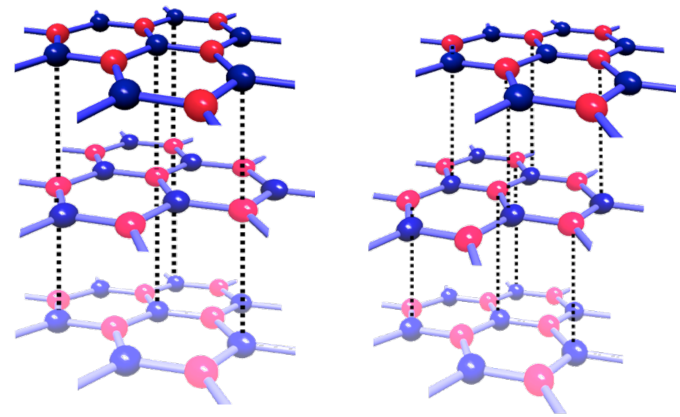
→ rich phase diagram

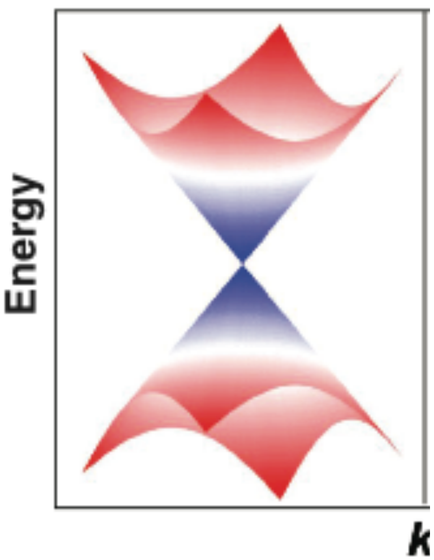
- Fantastic quantum Hall platform
  - multicomponent
  - lowest Landau level is 2L-degenerate (L=# layers)
  - extremely tunable (density, B_t→spin, $B_\perp$→orbital, $E_\perp$→layer)

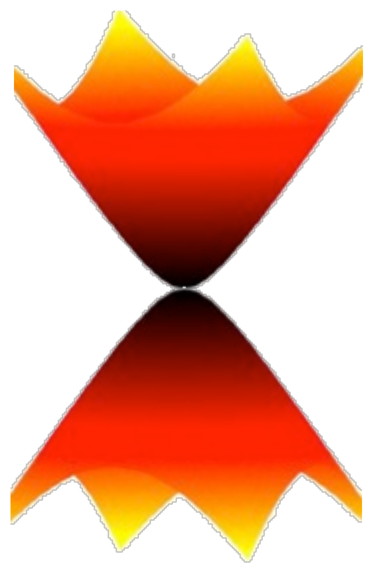
1, 2, 3…

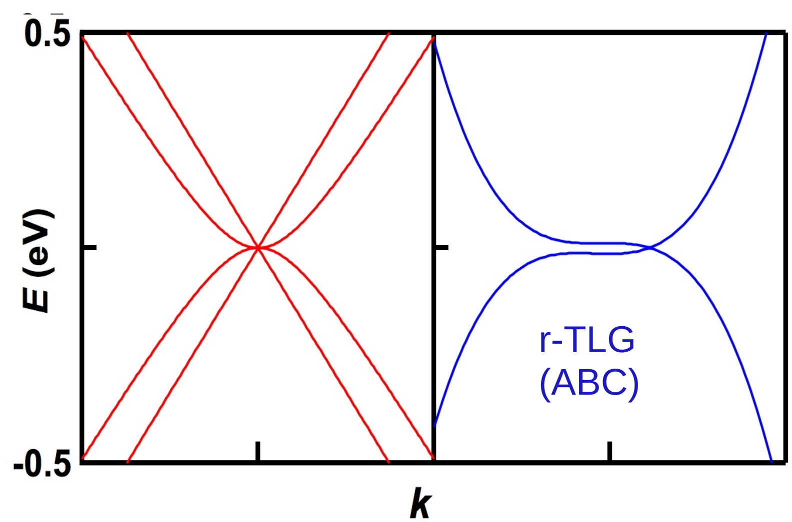












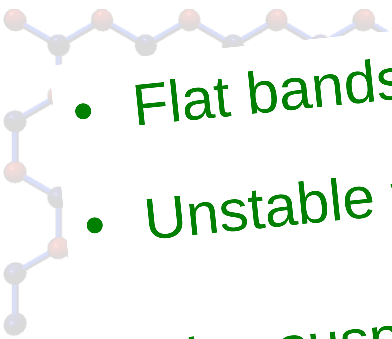
$$E = \hbar v_F k$$

$$E = \frac{\hbar^2 k^2}{2m^*}$$

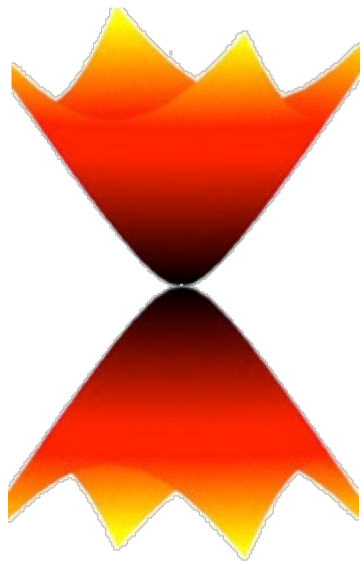
“2+1”

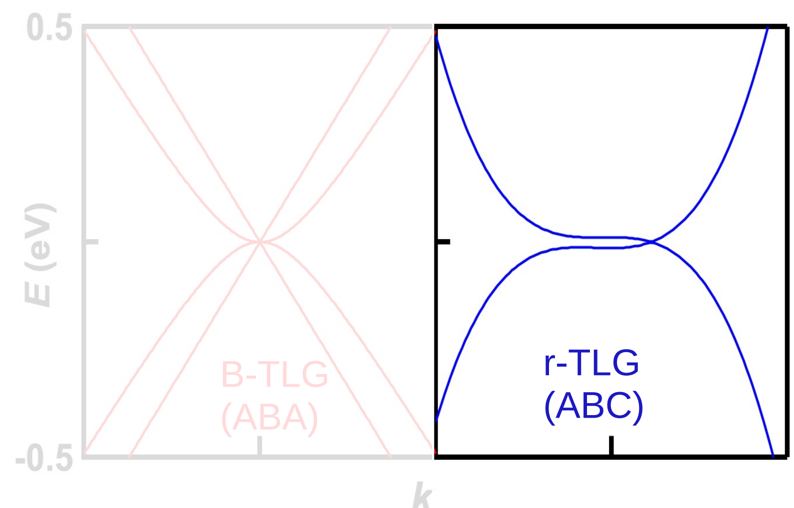
$$E = \frac{\hbar^3 v_F^3 k^3}{t_\perp^2}$$

1, 2, 3…



- Flat bands and large density of states at DP
- Unstable to electronic interactions →symmetry broken states
- Use suspended samples to minimize screening by substrate





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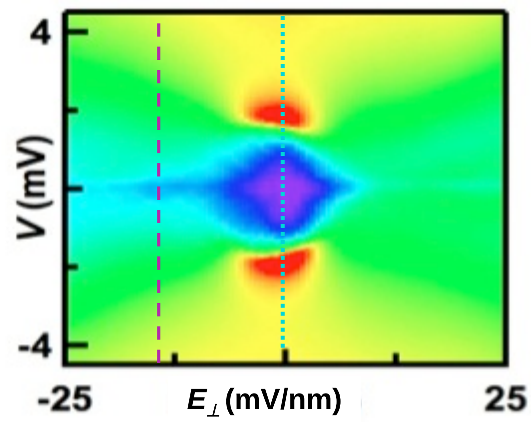
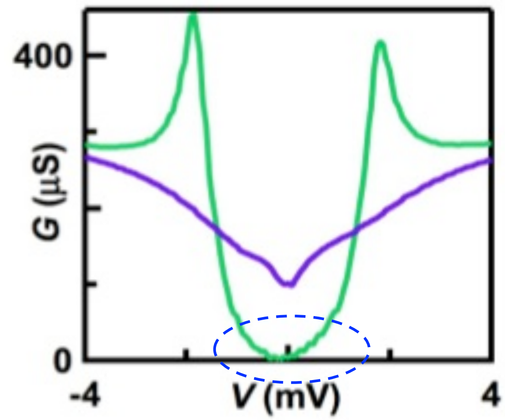
"2+1"

$$E = \frac{\hbar^3 v_F^3 k^3}{t_\perp^2}$$

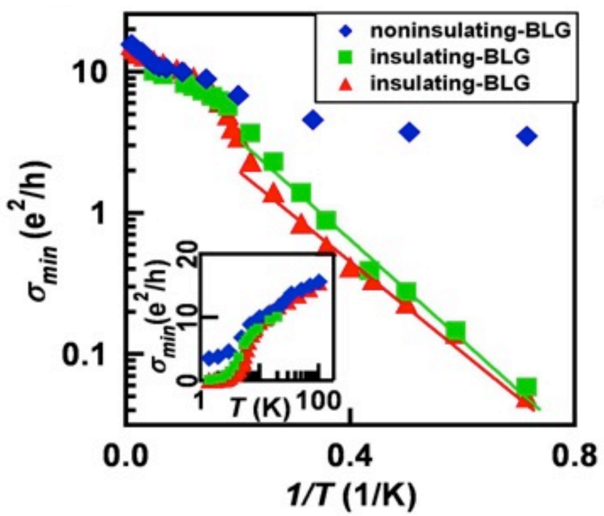
Gapped Insulating State in BLG

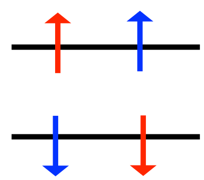
dI/dV vs. Electric field and source-drain bias at charge neutrality point





- **intrinsic gapped** ground state ~ 2meV
- Gap can be closed by electric field of either polarity ~ 12 meV/nm.
- Layer antiferromagnet



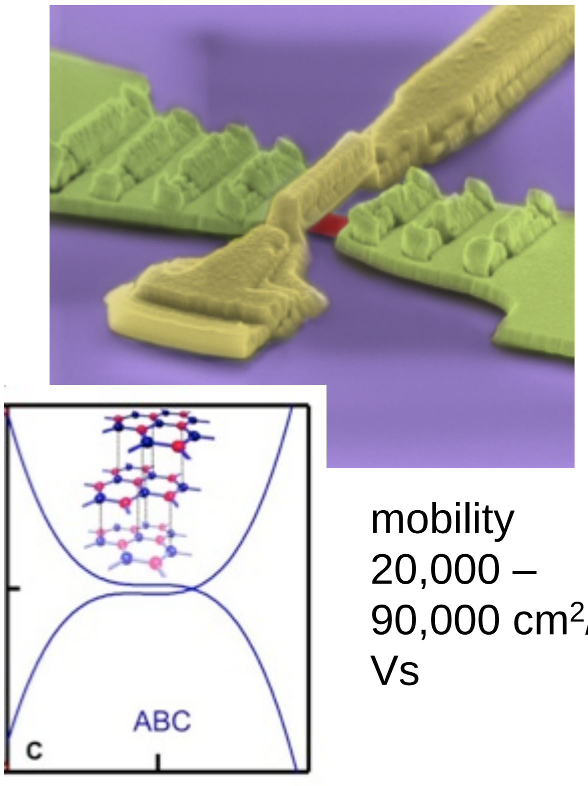


W. Bao, J. Velasco Jr, F. Zhang, L. Jing, B. Standley, D. Smirnov, M. Bockrath, A. MacDonald, C.N. Lau, Proc. Nat. Acad. Sci., 109, 10802 (2012).

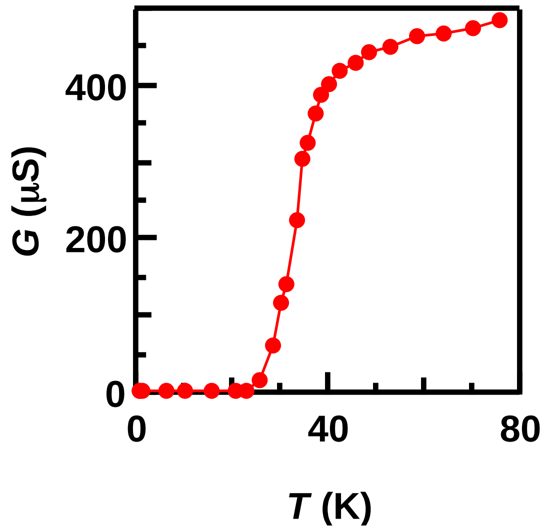
J. Velasco Jr., L. Jing, W. Bao, Y. Lee, P. Kratz, V. Aji, M. Bockrath, C.N. Lau, C. Varma, R. Stillwell, D. Smirnov, Fan Zhang, J. Jung, A.H. MacDonald, Nature Nanotechnol., 7, 156 (2012).

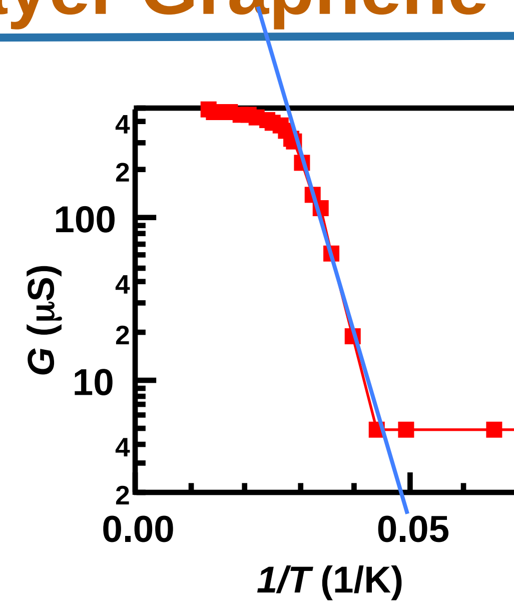
See also results from Yacoby group, Schonenberger group, van wees group and Morpurgo group.

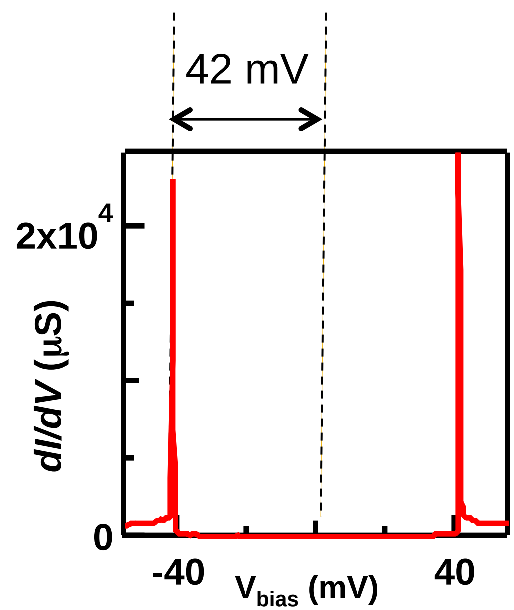
Dual-Gated Suspended ABC Trilayer Graphene



mobility 20,000 – 90,000 cm²/Vs







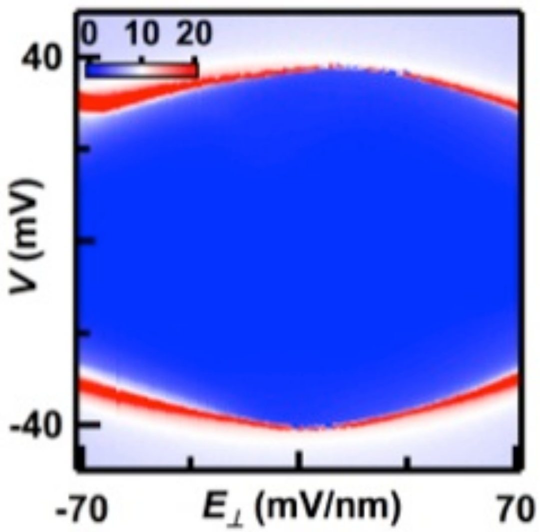
- Metal – insulator transition, T_c ~ 35K
- Thermal activation measurement yields

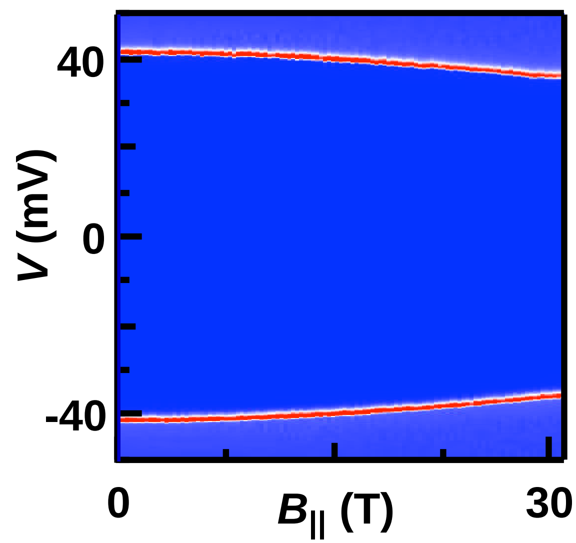
  Δ ~ 41 meV

- *G(V_bias)* curves at $E_{\perp}=n=0$ yield *Δ* ~ 42 meV

Effect of electric and magnetic fields

Differential conductance *G* vs source drain bias *V* at *n=0*





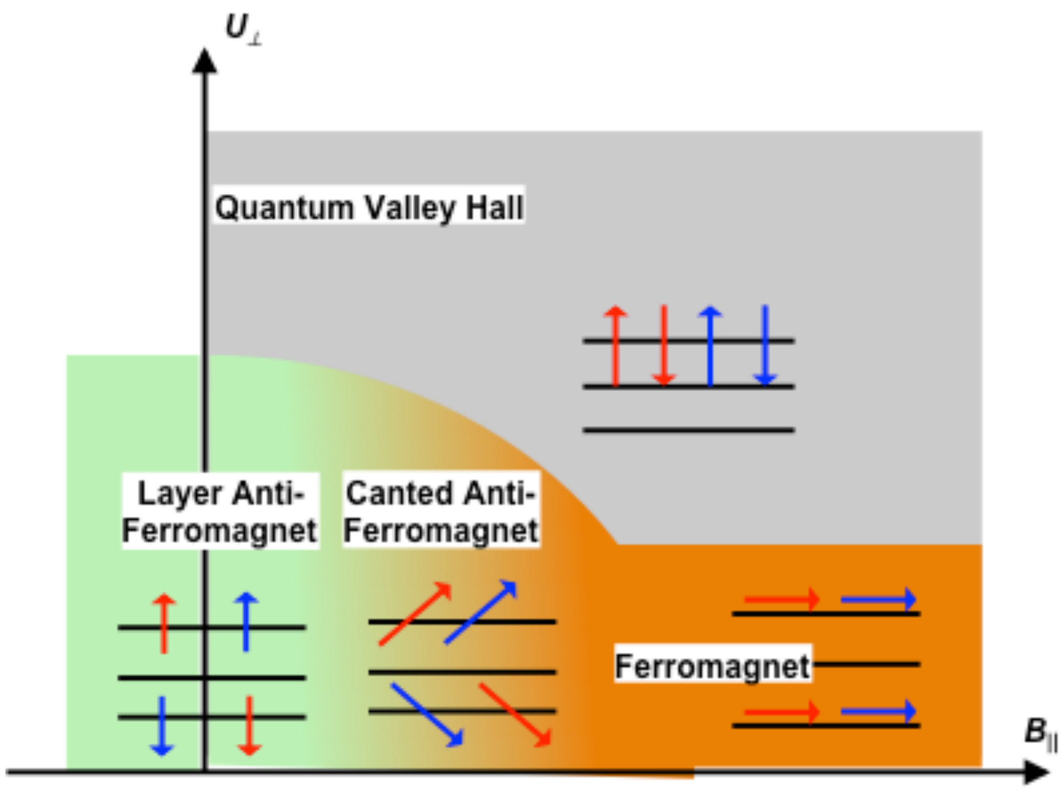
- gap educed symmetrically by $|E_{\perp}|$

→ not layer polarized; arises from electronic interactions

- gap reduced by parallel magnetic field at 30T

Y. Lee, D. Tran, K. Myhro, J. V. Jr., N. Gillgren, C. N. Lau, Y. Barlas, J. M. Poumirol, D. Smirnov, and F. Guinea, Nature Communications, 5, 5656 (2014)

Proposed Phase Diagram



Y. Lee, D. Tran, K. Myhro, J. V. Jr., N. Gillgren, C. N. Lau, Y. Barlas, J. M. Poumirol, D. Smirnov, and F. Guinea, Nature Communications, 5, 5656 (2014)

Layer-dependent Gap

- Spontaneous and single-particle gaps
- why stop at 3…

$$\alpha \sim \frac{\text{Coulomb Energy}}{\text{Fermi Energy} \sim k^p} \sim \kappa^{-1} n^{-\frac{p-1}{2}}$$

n=charge density (10^{10} cm^{-2})
κ=dielectric constant

	Dispersion	α (κ=1)	Interaction-induced Gap	T_c
GaAs/AlGaAs	$E \sim k^2$	(10-50)/√n		
Single Layer Graphene	$E \sim k$	2.2	<0.1meV	N/A
Bilayer Graphene	$E \sim k^2$	70/√n	2-3 meV	5K
ABC-stacked Trilayer	$E \sim k^3$	1500/n	40 meV	36K
ABC-stacked N-layer	$E \sim k^N$	gigantic	gigantic?	RT?

Interaction-induced gap in tetra-layer?

Outline

- Symmetry-broken Ground State in Few Layer Graphene
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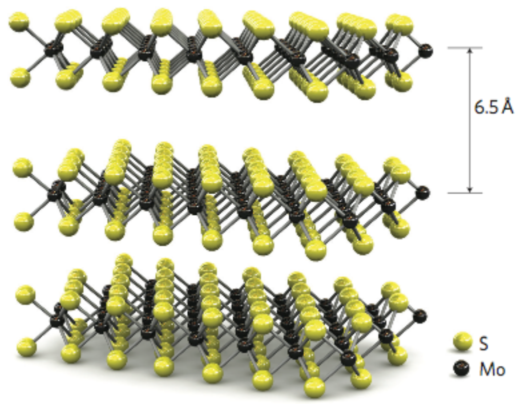
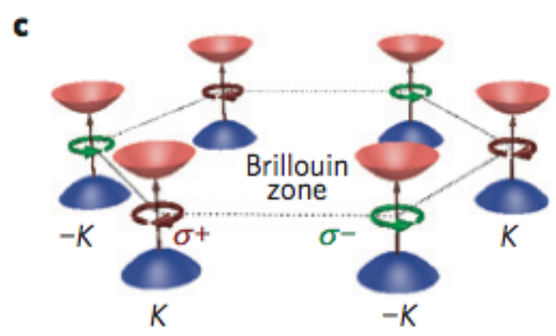
MoS_2

- gapped, On/Off ratio >10^6
- direct-to-indirect band gap transition as function of thickness
- valley physics



Radisavljevic et al, Nat. Nanoetchnol. 2011.

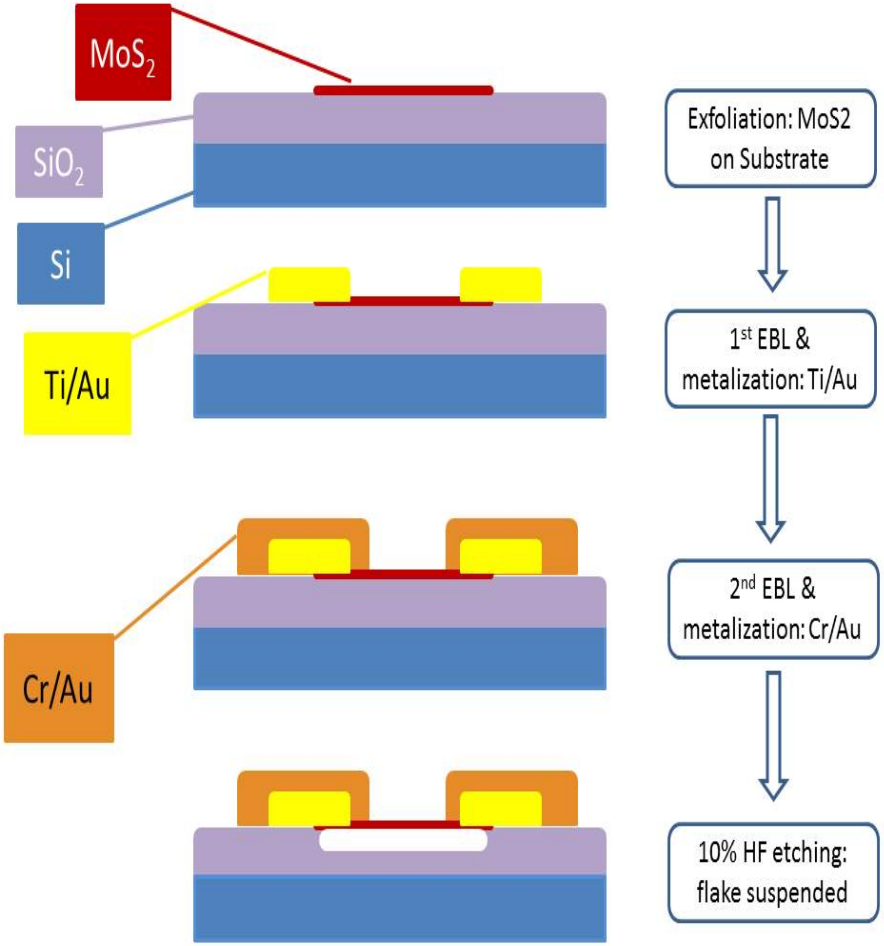
But
Mobility <~ 200 – 500 cm^2/Vs

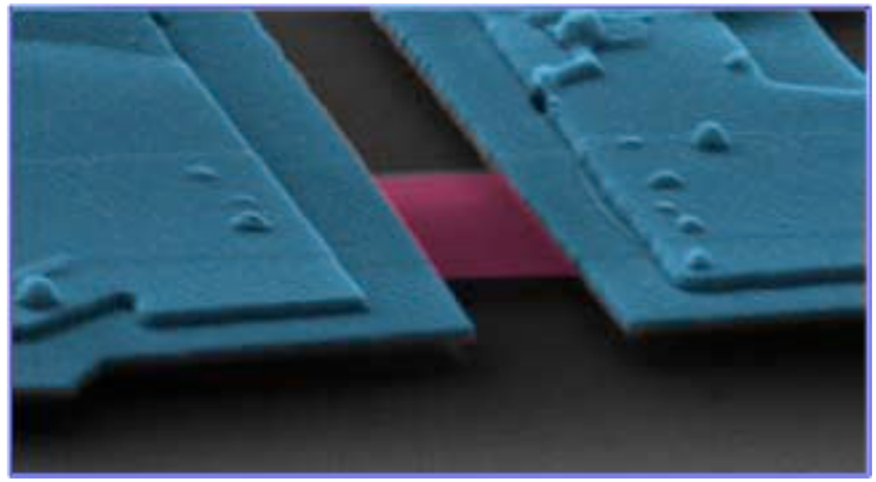


Wu et al, Nat. Phys. 2013.

and many others

Suspending MoS_2





- the mobility is even lower, 0.1 -50 cm^2/Vs
- gas annealing → 200 cm^2/Vs
- Removing substrates does not significantly improve mobility
- Other mobility bottlenecks:
  - Schottky barriers at contact
  - impurity scattering
  - defects

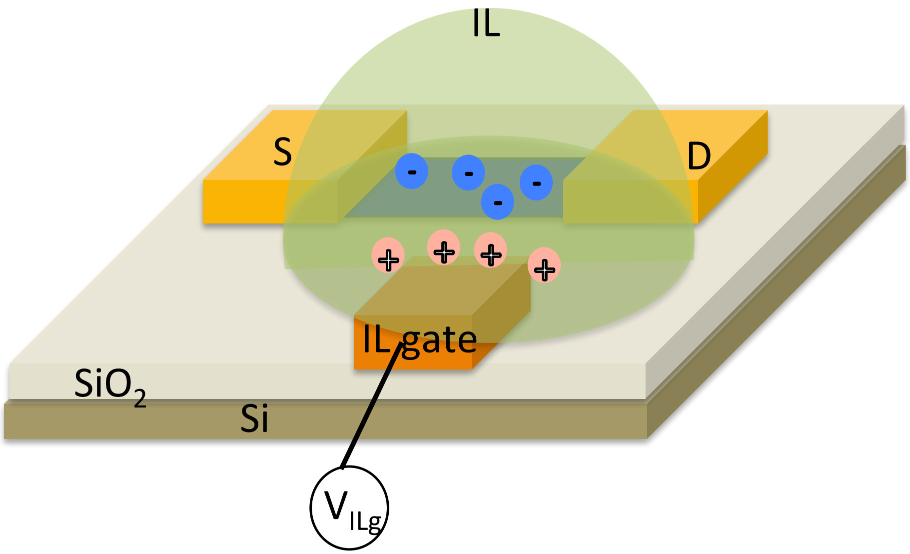
F. Wang, M. Gray, P. Stepanov and C.N. Lau, Nanotechnology, in press (2015)

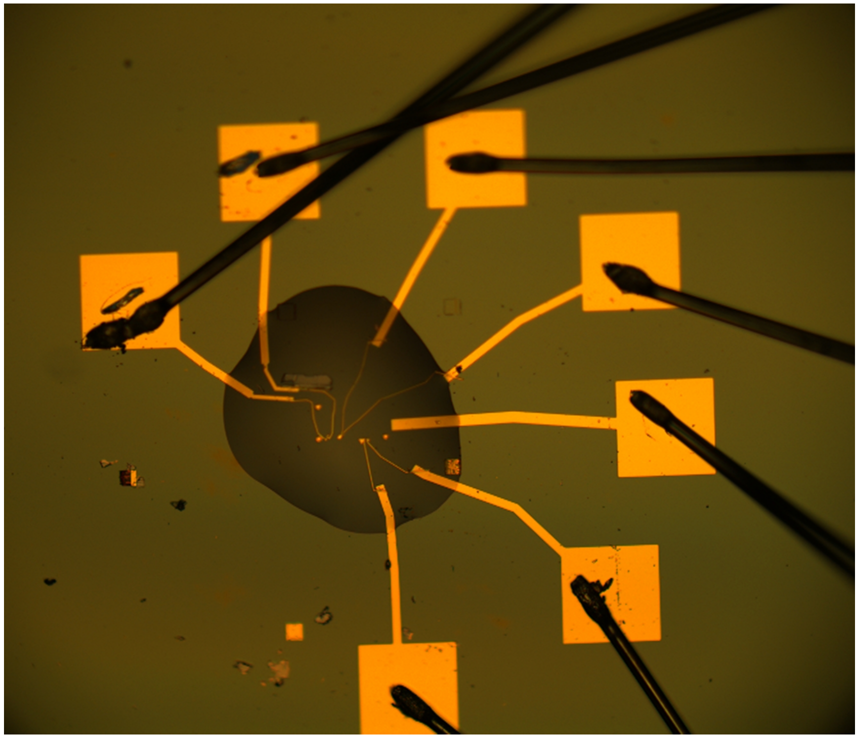
see recent work from Columbia group

Ionic liquid gating of MoS_2

In collaboration with Robert Haddon at UCR

- Ionic liquids are molten salts with low melting point
- can induce high carrier density (up to 10^{14} cm^{-2})
- use DEME-TFSI (N,N-diethyl-N-(2-methoxyethyl)-N-methylammonium bis-(trifluoromethylsulphonyl)-imide)





F. Wang, M. Gray, P. Stepanov and C.N. Lau, in preparation (2015)

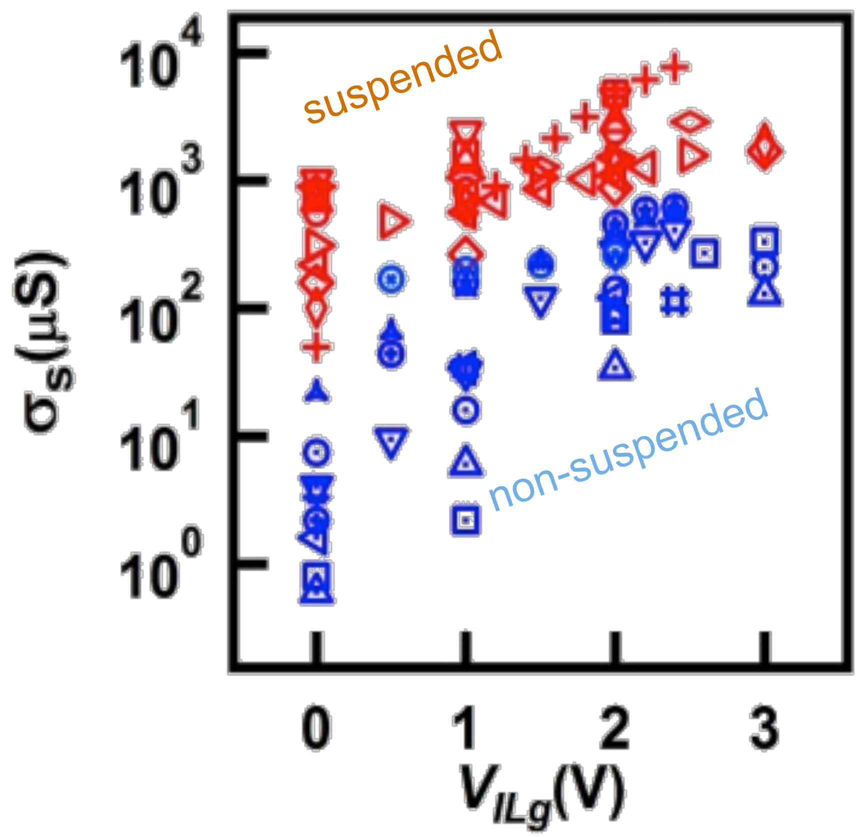
Comparing Suspended and non-suspended devices

Performed IL gating of 9 suspended and 9 substrate-supported samples

- use DEME-TFSI (N,N-diethyl-N-(2-methoxyethyl)-N-methylammonium bis-(trifluoromethylsulphonyl)-imide)

- all suspended devices are more conductive by 1-4 orders of magnitude

→ IL gating is more effective in free-standing devices



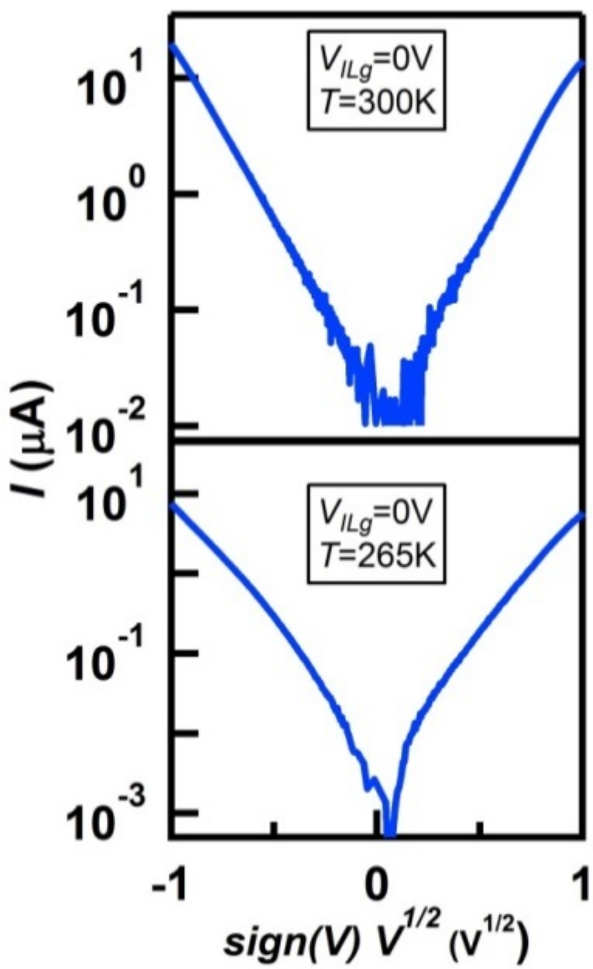
Mechanism:

1. Higher charge density
2. Better screening that reduce Schottky barriers and impurity scattering

F. Wang, M. Gray, P. Stepanov and C.N. Lau, Nano Lett. (2015)

Transport Mechanism

V_{ILg}=0



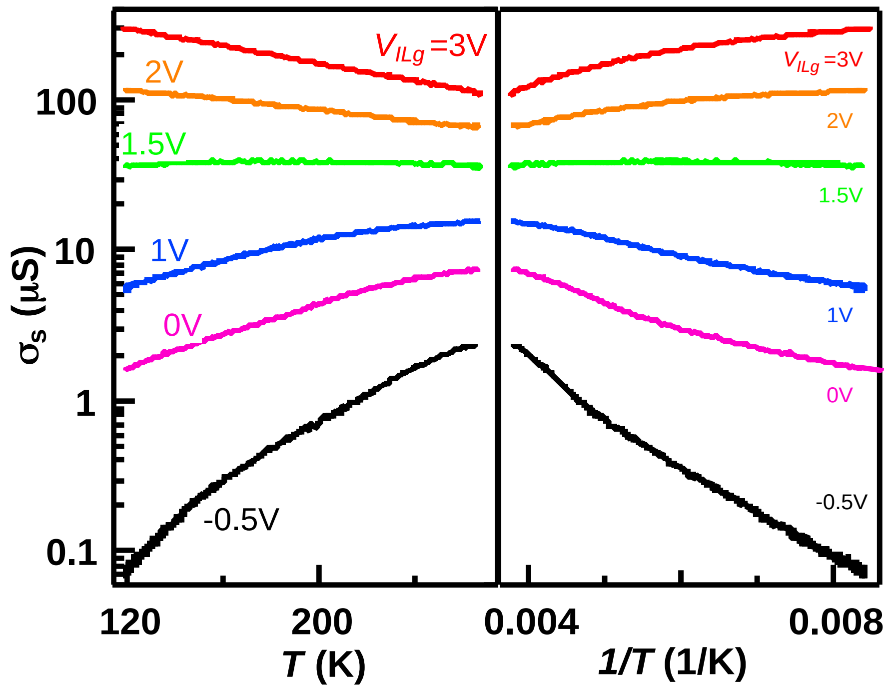
Schottky emission at MoS_2-electrode interfaces

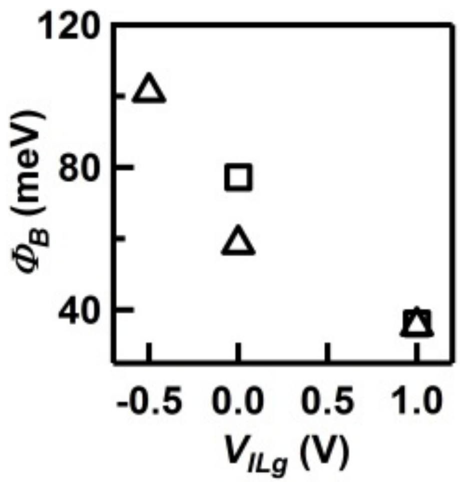
$$I \propto \exp\left(\frac{a\sqrt{V} - \Phi_B}{k_B T}\right)$$

$$a = e\sqrt{\frac{e}{4\pi\varepsilon_0\varepsilon_r d}}$$

slope yields $\varepsilon_r \sim 11$
→ dielectric constant of DEME-TFSI ~ 14.5

IL-tuned Metal Insulator Transition

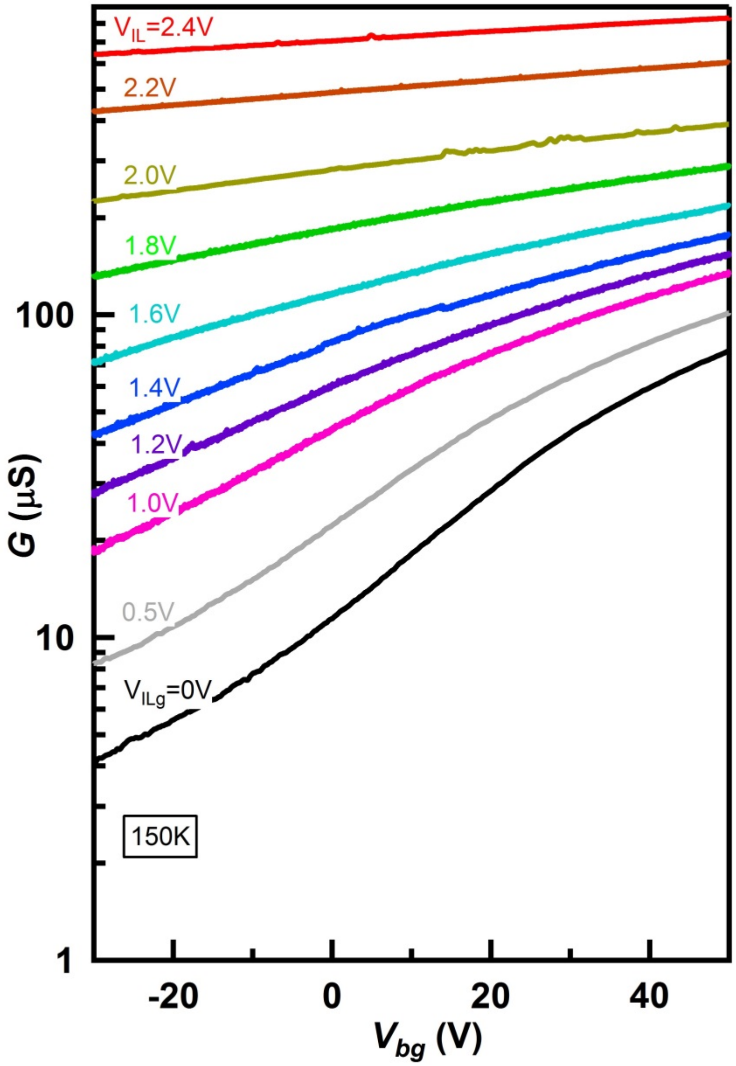


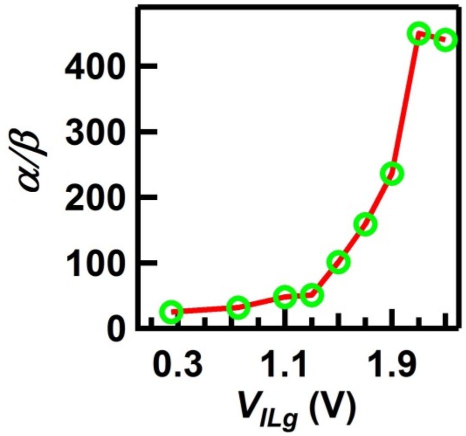


- **metal insulator transition observed as V_{ILg} is tuned**
- At small V_{ILg}, transport via thermal activation

$$I \propto \exp\left(\frac{a\sqrt{V} - \Phi_B}{k_B T}\right) \qquad a = e\sqrt{\frac{e}{4\pi\varepsilon_0\varepsilon_r d}}$$ obtained from I-V curves

Ionic liquid gating of Suspended MoS_2





- **ratio of ionic liquid gate to back gate: up to 400**
- >~ coupling efficiency of substrate-supported devices
- allow extremely high doping density

F. Wang, M. Gray, P. Stepanov and C.N. Lau, Nano Lett. (2015)

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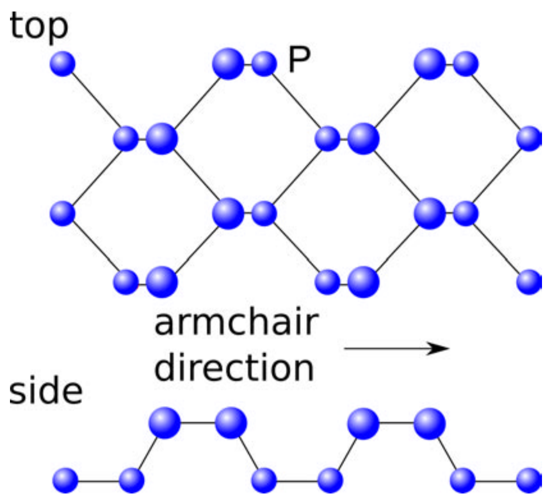
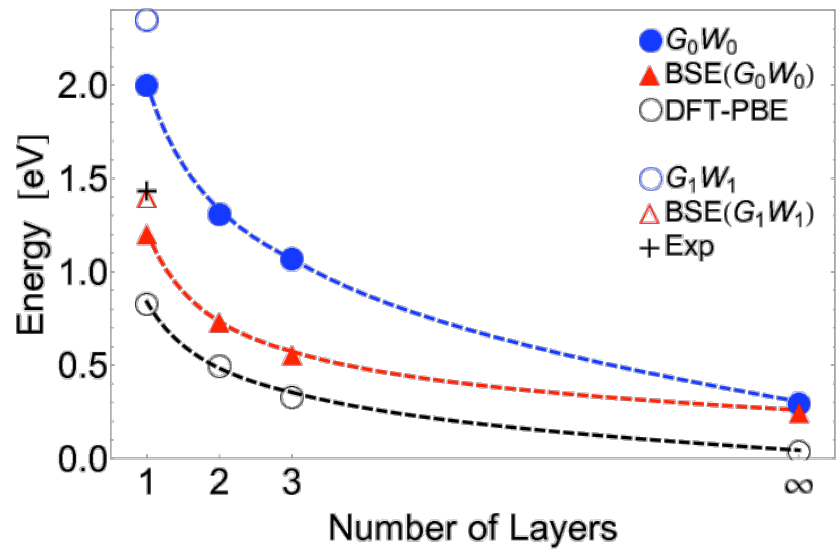
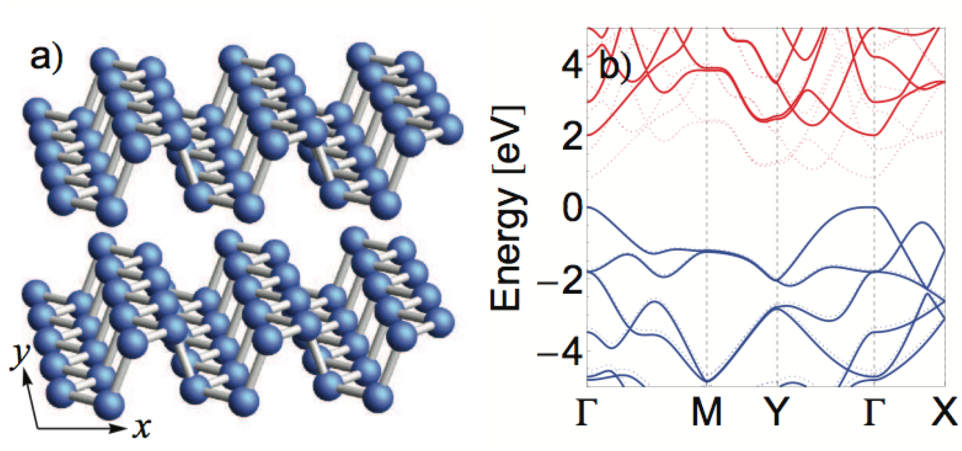
Black Phosphorus



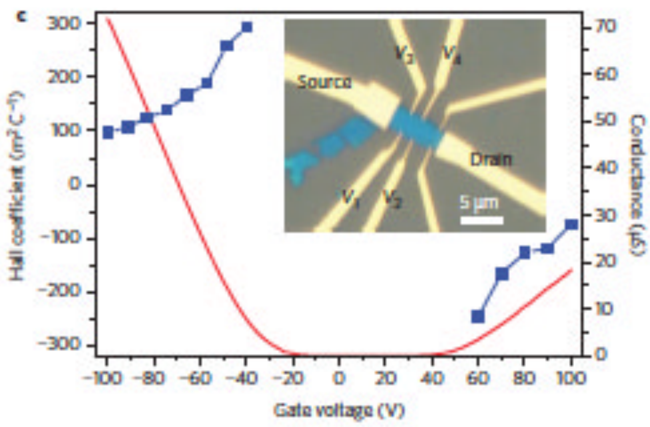




- Puckered atoms within layers
- Anisotropic
- Thickness dependent band gap, 0.3 - 2 eV
- Direct band gap for all thickness

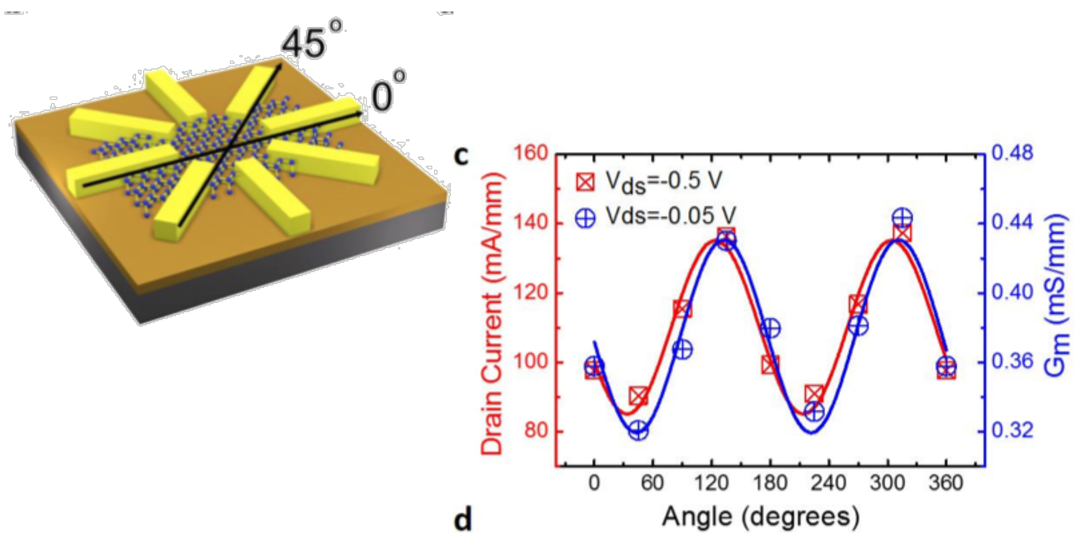
Tran et al, PRB 2014 Asahina & Morita, J. Phys. C, 1986

Few-Layer Black Phosphorus Transistors

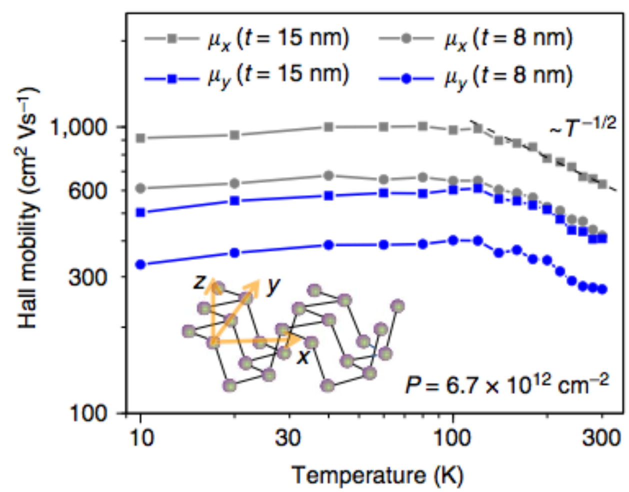


Li et al, Nature Nanotechnol 2014

- ambipolar transport
- gapped, on/off ration ~10^5
- Anisotropic Transport
- Mobility ~100-1000 cm^2/Vs for thickness ~2 – 20 nm

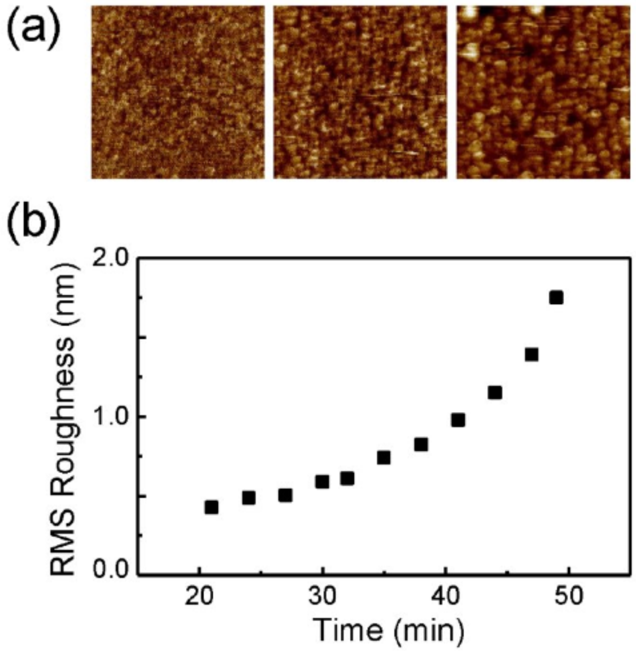


Liu et al, ACS Nano 2014

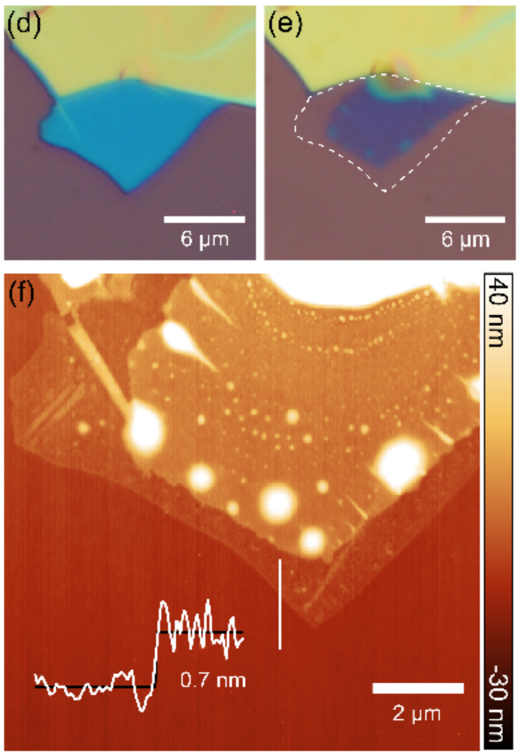


Xia et al, Nature Comm. 2014

Challenges



Kroenig et al, APL 2014



Island et al, 2D Materials 2014

Instability in air

- react with water and O_2 to form phosphoric acid
- reaction accelerated by light

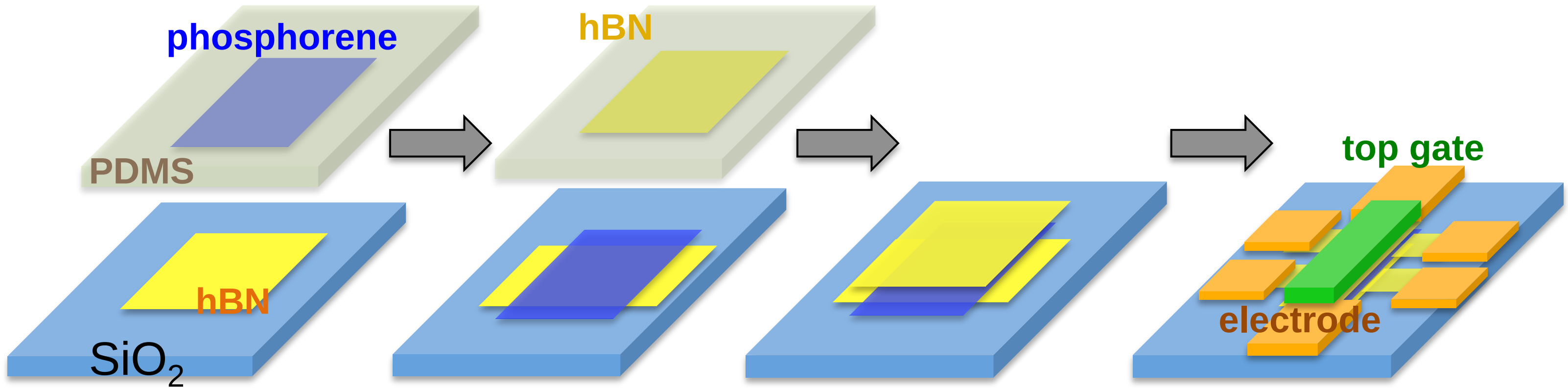
Favor et al, arxiv 2014

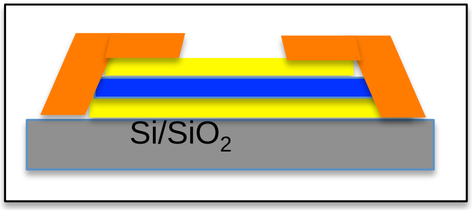
Challenges

Mission Impossible?

This device will self-destruct in 1 hour

Device Fabrication



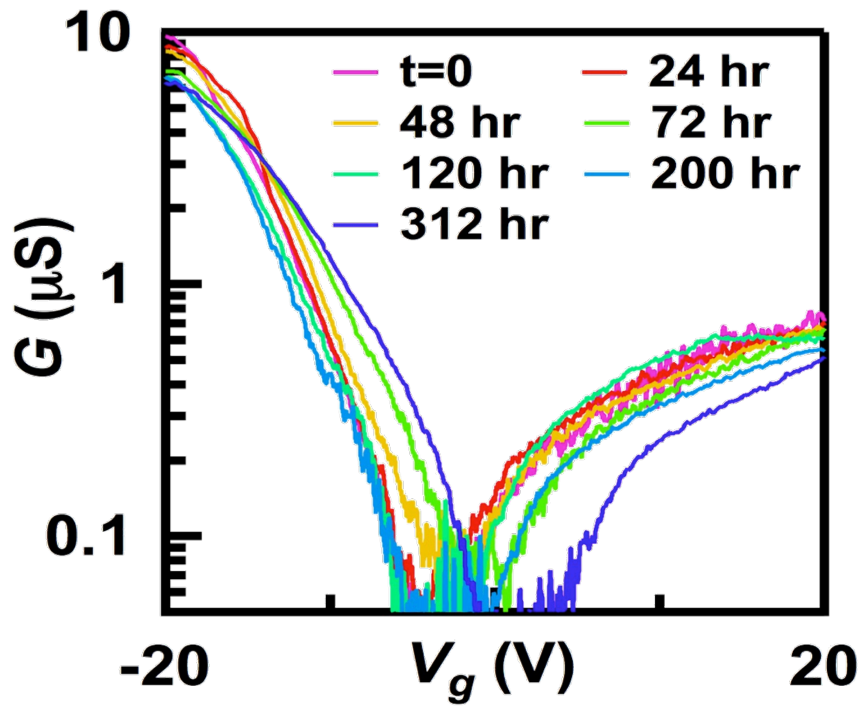


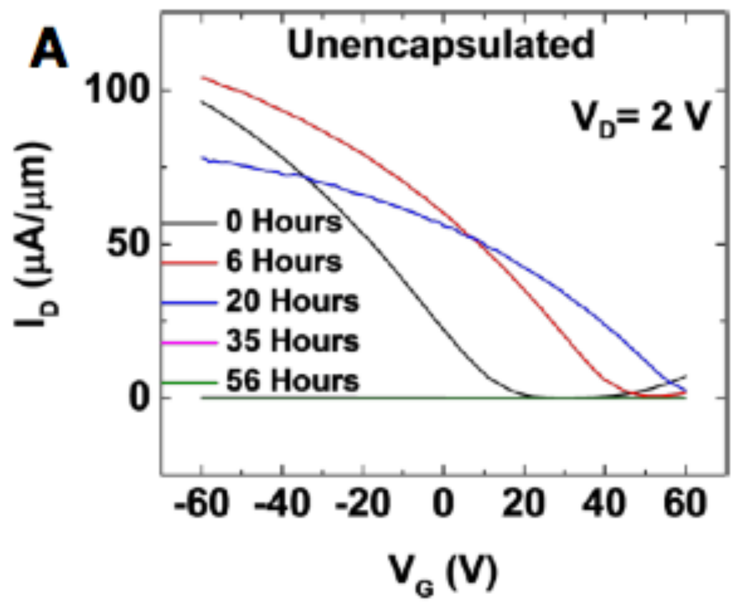
- Dry transfer to form hBN/few-layer phosphorene/hBN heterostructure sandwiches
- etch to expose edges of phosphorene
- 1D metallic contact to 2D layers

Columbia group, Science 2013

Device Stability

Encapsulated in hBN (our data)



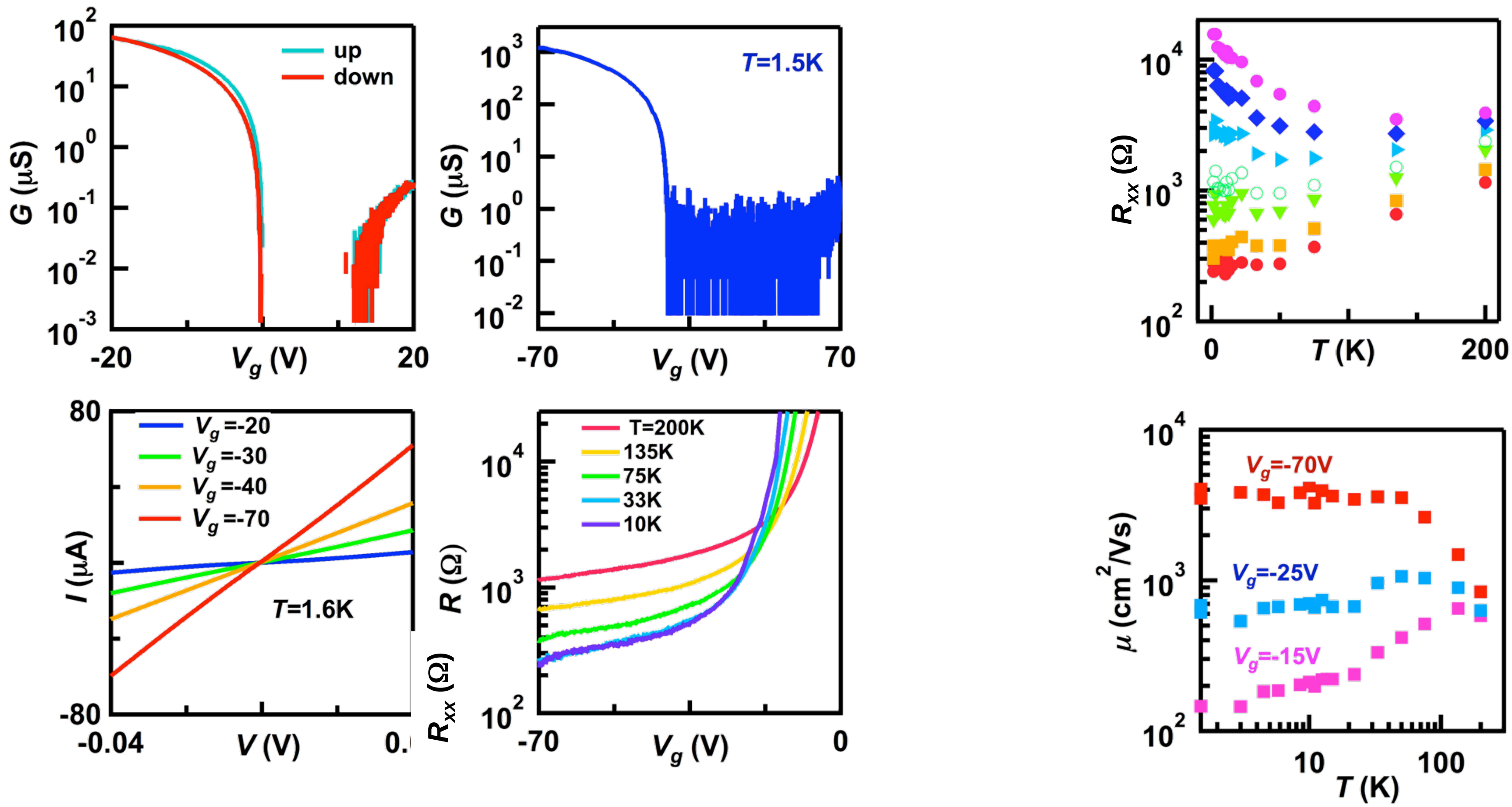


Wood et al, Nano Letters 2014

- Device left in air for 2 weeks
- Slight shift in charge neutrality point
- Only slight decrease in conductance & mobility

N. Gillgren, D. Wickramaratne, Y. Shi, T. Espiritu, J.Yang, J. Hu, J. Wei, X. Liu, Z. Mao, K. Watanabe, T. Taniguchi, Marc Bockrath, Yafis Barlas, R. K. Lake, C.N. Lau, 2D Materials, in press (2014)

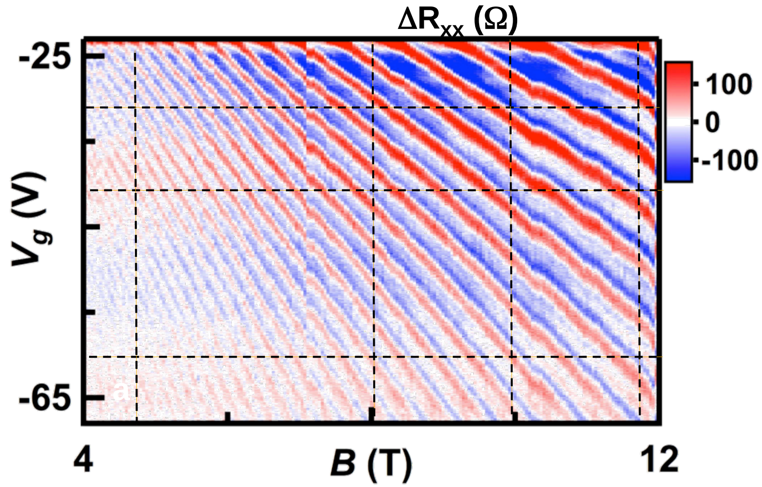
Device mobility



- Ambipolar transport
- On/off ratio ~ 10^5
- linear I-V → ohmic contact

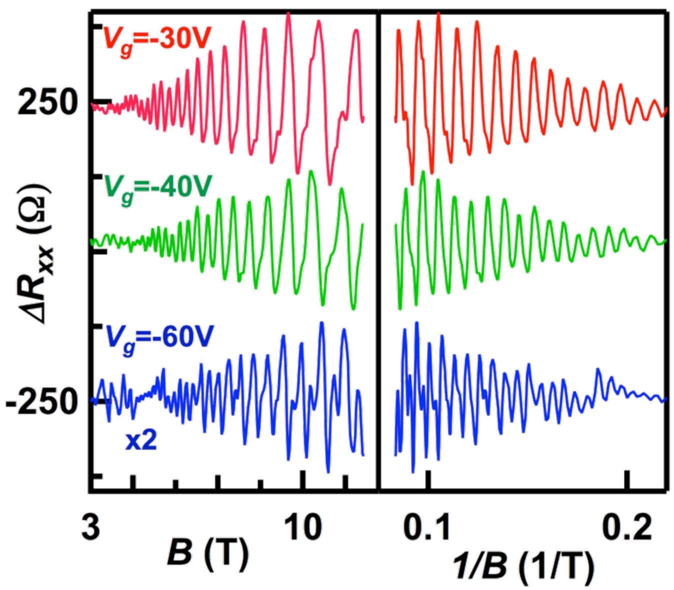
- Metal-insulator transition
- highly hole-doped: metallic, μ up to 4000
- towards band edge: insulating, μ ↓ with T

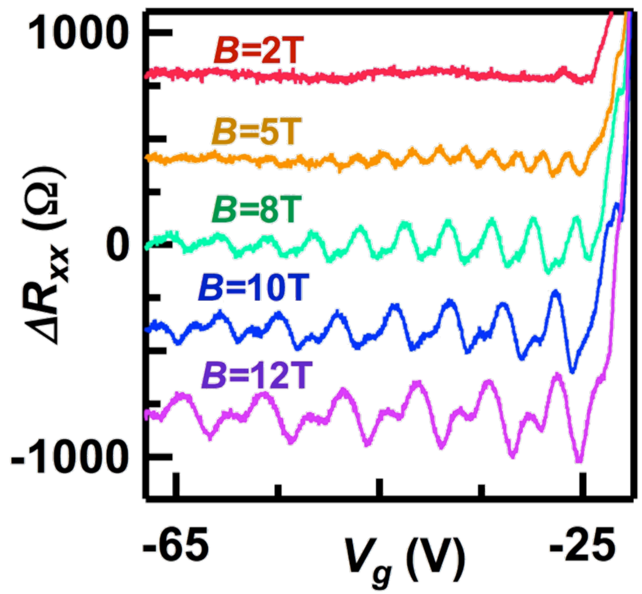
Quantum Oscillations



R_{xx} with smooth background subtracted

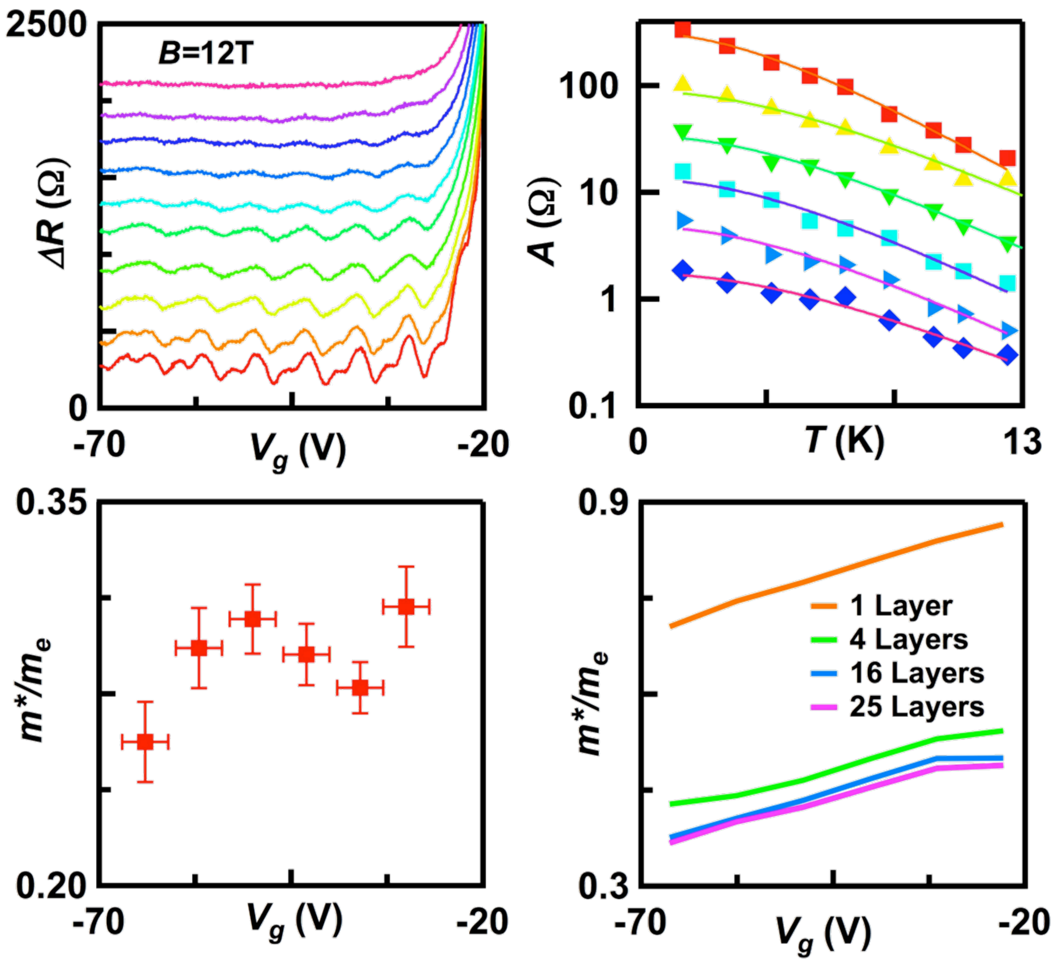
- oscillations periodic in 1/B
- oscillations periodic in V_g ~n
- doubling frequency in for B>8T → Zeeman splitting





N. Gillgren, D. Wickramaratne, Y. Shi, T. Espiritu, J.Yang, J. Hu, J. Wei, X. Liu, Z. Mao, K. Watanabe, T. Taniguchi, Marc Bockrath, Yafis Barlas, R. K. Lake, C.N. Lau, 2D Materials, in press (2015)

Temperature Dependence Quantum Oscillations



Oscillations' amplitude dependence on T

$$A(T) = \frac{CT}{\sinh(bT)}$$

$$b = \frac{2\pi^2 k_B m^*}{\hbar e}$$

- effective mass of charge carriers ~0.25 to 0.31 m_e as Fermi energy increases towards band edge
- agree with DFT calculations within 50%

N. Gillgren, D. Wickramaratne, Y. Shi, T. Espiritu, J.Yang, J. Hu, J. Wei, X. Liu, Z. Mao, K. Watanabe, T. Taniguchi, Marc Bockrath, Yafis Barlas, R. K. Lake, C.N. Lau, 2D Materials, in press (2014)

Fast Moving Field

1. arXiv:1412.1357 [pdf]

   High quality sandwiched black phosphorus heterostructure and its quantum oscillations
   Xiaolong Chen, Yingying Wu, Zefei Wu, Shuigang Xu, Lin Wang, Yu Han, Weiguang Ye, Tianyi Han, Yuheng He, Yuan Cai, Ning Wang
   Subjects: **Materials Science (cond-mat.mtrl-sci)**

2. arXiv:1412.1274 [pdf]

   Accessing the transport properties of pristine few-layer black phosphorus by van der Waals passivation in inert atmosphere
   Rostislav A. Doganov, Eoin C.T. O'Farrell, Steven P. Koenig, Yuting Yeo, Angelo Ziletti, Alexandra Carvalho, David K. Campbell, David F. Coker, Kenji Watanabe, Takashi Taniguchi, Antonio H. Castro Neto, Barbaros Özyilmaz
   Subjects: **Mesoscale and Nanoscale Physics (cond-mat.mes-hall)**; Materials Science (cond-mat.mtrl-sci)

3. arXiv:1412.1191 [pdf]

   Electrical characterization of fully encapsulated ultra thin black phosphorus-based heterostructures with graphene contacts
   Ahmet Avsar, Ivan J. Vera-Marun, Tan Jun You, Kenji Watanabe, Takashi Taniguchi, Antonio Helio Castro Neto, Barbaros Ozyilmaz
   Subjects: **Mesoscale and Nanoscale Physics (cond-mat.mes-hall)**

4. arXiv:1412.0842 [pdf, other]

   Broadband Electrically Detected Magnetic Resonance Using Adiabatic Pulses
   F. M. Hrubesch, G. Braunbeck, A. Voss, M. Stutzmann, M. S. Brandt
   Subjects: **Mesoscale and Nanoscale Physics (cond-mat.mes-hall)**

5. arXiv:1412.0717 [pdf]

   Gate Tunable Quantum Oscillations in Air-Stable and High Mobility Few-Layer Phosphorene Heterostructures
   Nathaniel Gillgren, Darshana Wickramaratne, Yanmeng Shi, Tim Espiritu, Jiawei Yang, Jin Hu, Jiang Wei, Xue Liu, Zhiqiang Mao, Kenji Watanabe, Takashi Taniguchi, Marc Bockrath, Yafis Barlas, Roger K. Lake, Chun Ning Lau
   Comments: minor correction of typos, equations and references
   Subjects: **Mesoscale and Nanoscale Physics (cond-mat.mes-hall)**

6. arXiv:1412.0355 [pdf]

   Toward Air-Stable Multilayer Phosphorene Thin-Films and Transistors
   Joon-Seok Kim, Yingnan Liu, Weinan Zhu, Seohee Kim, Di Wu, Li Tao, Ananth Dodabalapur, Keji Lai, Deji Akinwande
   Comments: 22 pages, 4 figures
   Subjects: **Materials Science (cond-mat.mtrl-sci)**

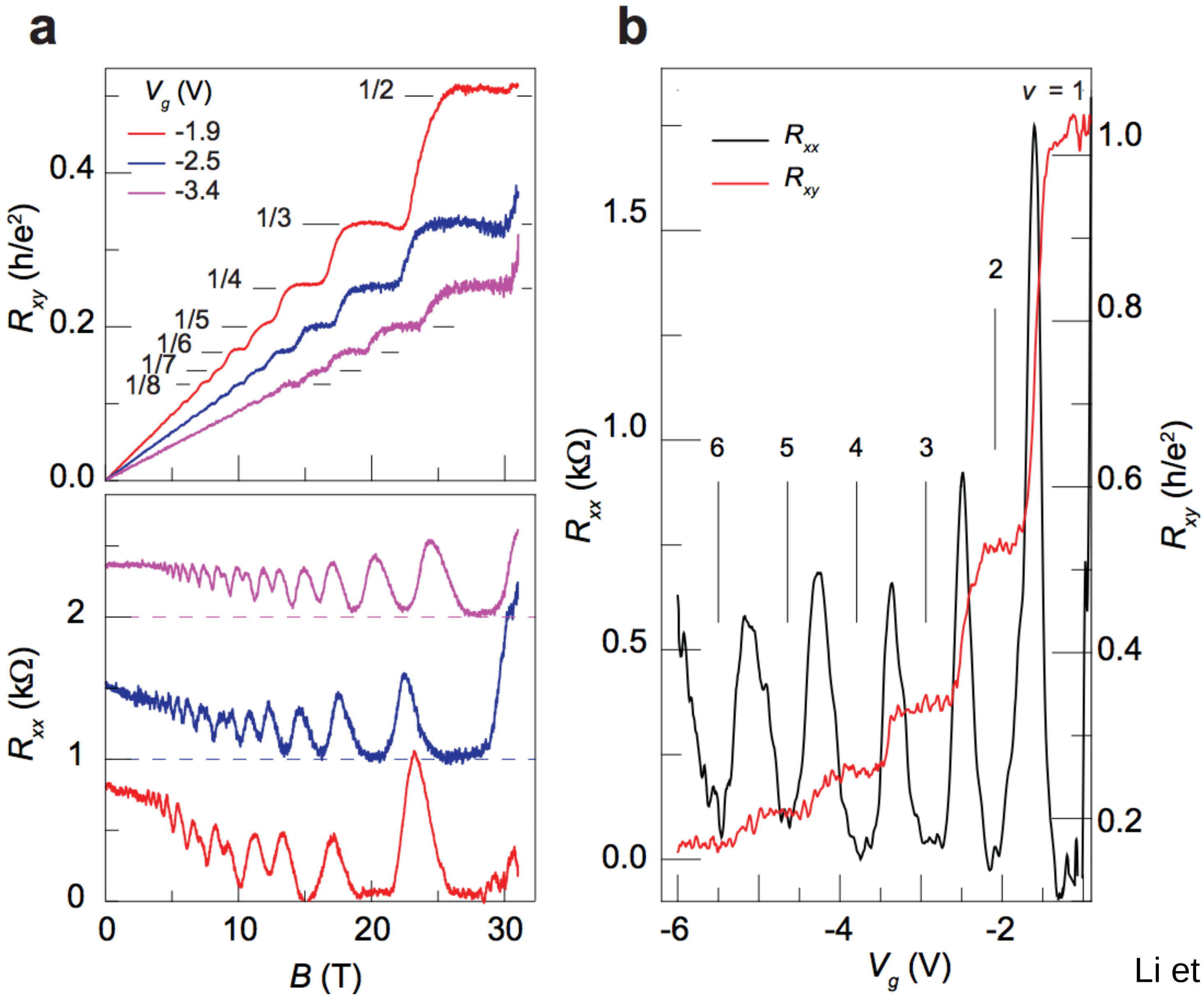
7. arXiv:1412.0259 [pdf, ps, other]

   Two-Dimensional Magnetotransport in a Black Phosphorus Naked Quantum Well
   V. Tayari, N. Hemsworth, I. Fakih, A. Favron, E. Gaufrès, G. Gervais, R. Martel, T. Szkopek
   Comments: 7 pages, 8 figures
   Subjects: **Mesoscale and Nanoscale Physics (cond-mat.mes-hall)**; Materials Science (cond-mat.mtrl-sci)

8. arXiv:1411.6572 [pdf]

   Quantum Oscillations in Black Phosphorus Two-dimensional Electron Gas
   Likai Li, Guo Jun Ye, Vy Tran, Ruixiang Fei, Guorui Chen, Huichao Wang, Jian Wang, Kenji Watanabe, Takashi Taniguchi, Li Yang, Xian Hui Chen, Yuanbo Zhang
   Subjects: **Mesoscale and Nanoscale Physics (cond-mat.mes-hall)**; Materials Science (cond-mat.mtrl-sci)

Report of Quantum Hall Effect



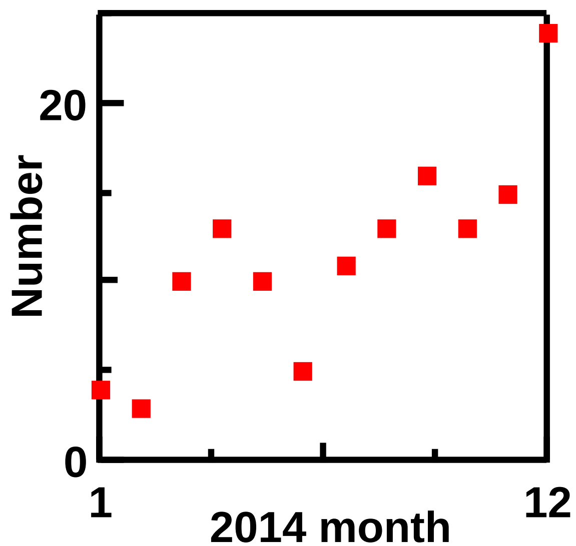
Li et al, arxiv 2015

Conclusion

- Few layer phosphorene has both high mobility and band gap
- Stable via hBN encapsulation

Outlook

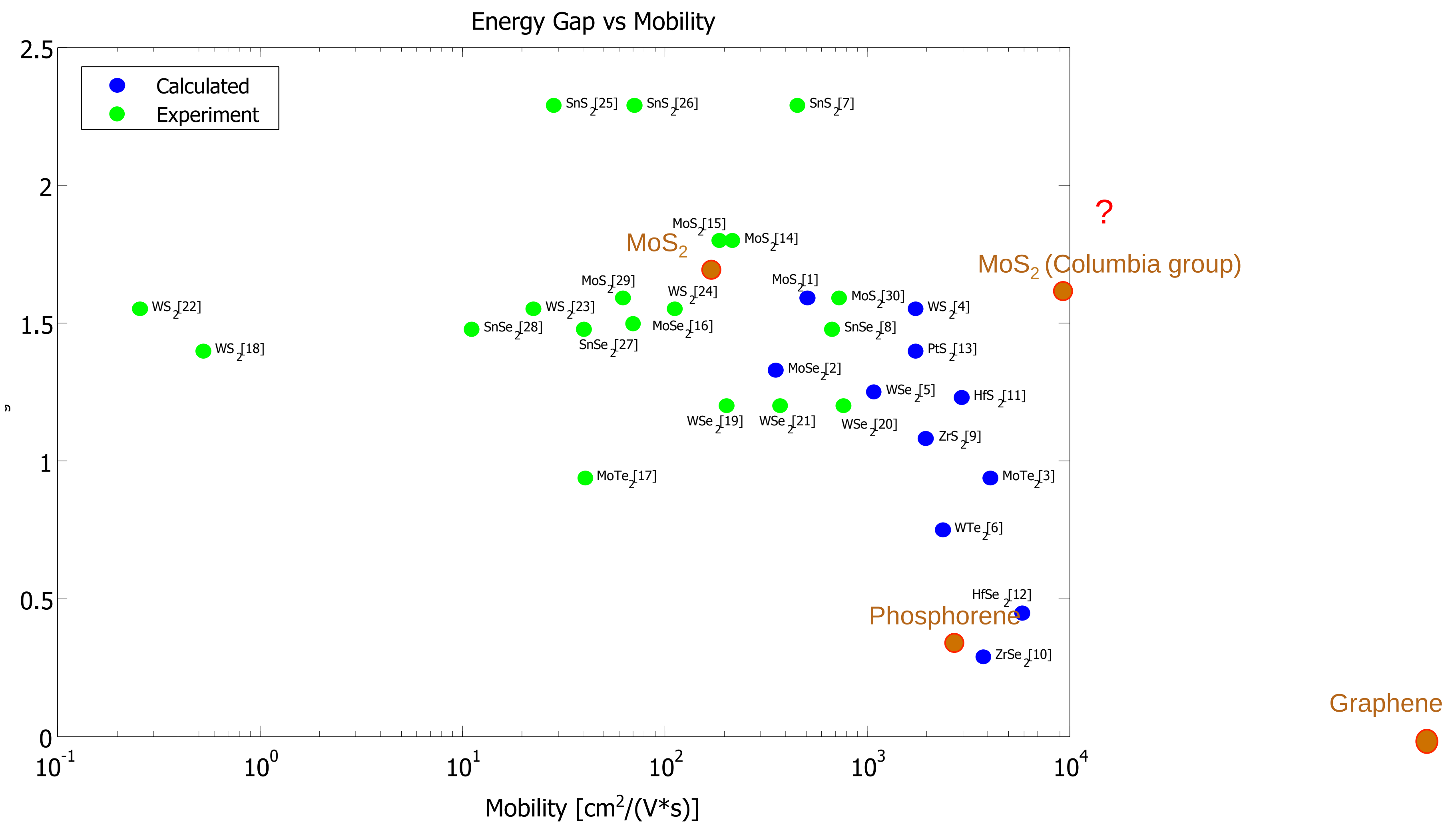
- Physics
  - strain-dependent band gap
  - large anisotropy (up to 60x, electrical and thermal transport, thermopower)
  - electric field effect
  - pressure-induced superconductivity?
  - (anisotropic?) quantum Hall effect
  - ….
- Electronics and optoelectronics
- hBN encapsulation of reactive 2D materials



see Cao et al, arXiv: 1502.03755

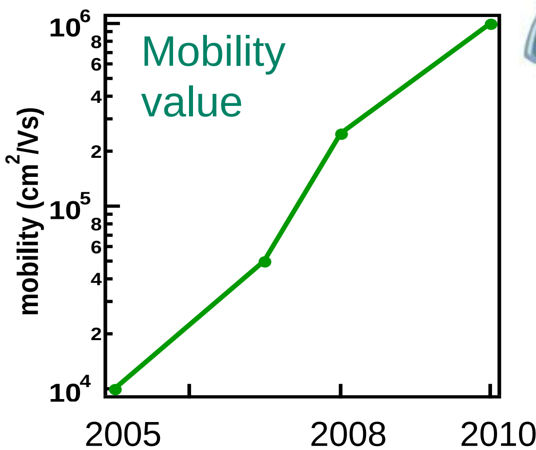
2D Materials: Gap vs Mobility

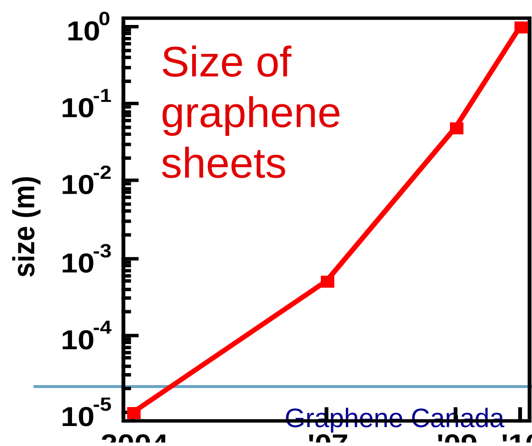
Courtesy: FAME center



What to ask a material scientist, part II

Yes, but does it scale?





Basic research
→ technology

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Yongjin Lee


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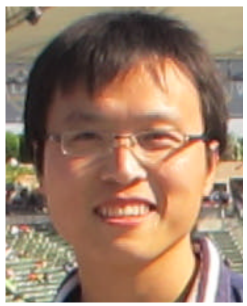
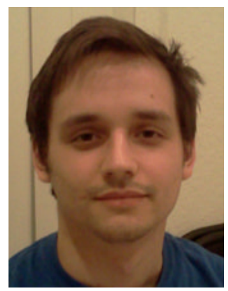

Yanmeng Shi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Petr Stepanov


Son Tran

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Thank You