Physics in Quasi-2D Materials for Spintronics Applications

Topological Insulators and Graphene

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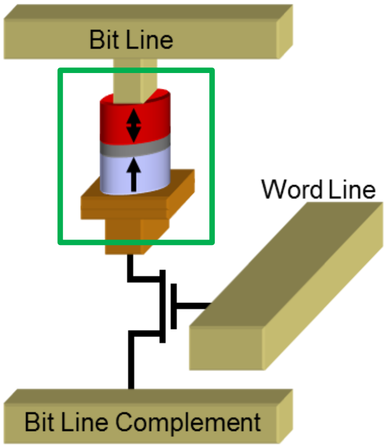
Spintronics

Electrical Properties (e.g., I, V, Q) ⟺ Magnetic Properties (e.g., M, spin)

Example: Spin-transfer torque MRAM (magnetoresistive random access memory)



- Magnetic tunnel junction
- Write – spin-transfer torque
- Read – tunneling magnetoresistance

Building blocks: Spin generation, modulation/control, detection, transport/conduction, amplification, etc.

Spintronics in Quasi-2D Materials

A. Spin-orbit coupling for spin generation

- Charge-spin conversion in topological insulators and spin-Hall metals

  Luqiao Liu (IBM), Anthony Richardella (PSU), Ion Garate (Sherbrooke), Nitin Samarth (PSU), Yu Zhu, Jonathan Sun (IBM)

  [1] L. Liu, et al., **Phys. Rev. B 91**, 235437 (2015).

  [2] L. Liu, C.-T. Chen and J. Z. Sun, **Nature Phys. 10**, 561 (2014).

B. Exchange coupling for spin modulation

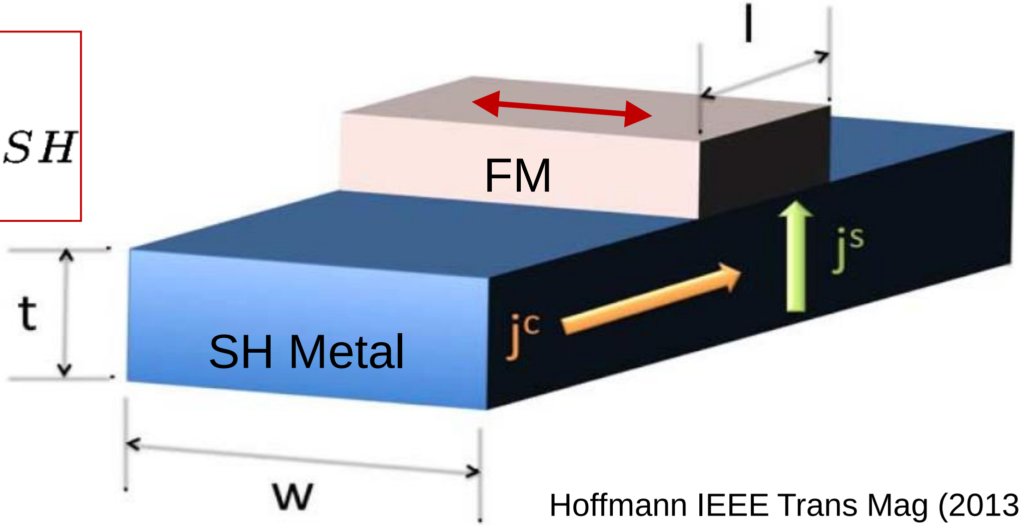
- Strong interfacial exchange field in graphene/magnetic-insulator heterostructures

  Peng Wei (MIT), Sunwoo Lee (Columbia), Florian Lemaitre, Lucas Pinel, Davide Cutaia, Yu Zhu (IBM), Wujoon Cha, Jim Hone (Columbia), Don Heiman (Northeastern), Ferhat Katmis, Jagadeesh Moodera (MIT)

  [3] P. Wei, et al., **Nature Mat. (2016)** , doi:10.1038/nmat4603

Spin-Orbit Coupling for Spin Generation

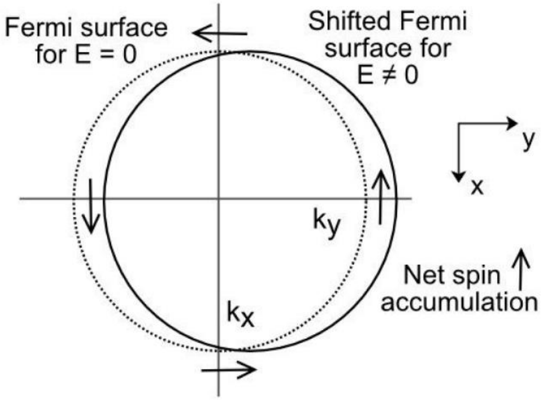
$$\frac{I^s}{I^c} = \frac{A^s}{A^c}\frac{j^s}{j^c} = \frac{l}{t}\Theta_{SH}$$



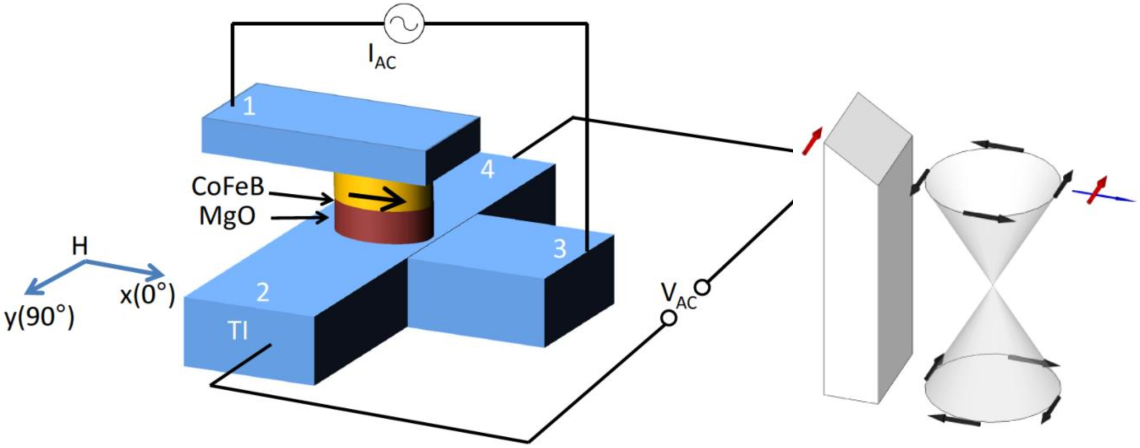
Hoffmann IEEE Trans Mag (2013)

- Boost spin current generation efficiency:
  - Isolate spin generation from charge current, bypassing MTJ breakdown limit
  - Magnetic moment manipulation for in-plane moment, assume $\theta_{SH} \sim 50\%$, $I_{c,MTJ-STT}/I_{c,SHE} \sim l/t \sim 5$ (junction size/SH metal thickness)
  - Not yet obvious how much benefit for perpendicular moment

Charge-Spin Conversion in TI: Spin-Polarized Tunneling



$$\boxed{\langle S_y \rangle^{\mathrm{D}}_{\mathrm{neq}} = -\frac{\hbar}{2ev_{\mathrm{F}}} j^{\mathrm{D}}_x}$$



- Topological surface states spin-momentum locking:

  * Quantify charge/spin conversion electrically

  * Energy dependence

  * Temperature dependence

  * Verify: symmetry

  * Verify: surface state vs. bulk state

- Method: 4-terminal spin-polarized tunneling technique

  * Tunneling (Inverse Edelstein effect)

  * Potentiometry (Edelstein effect)

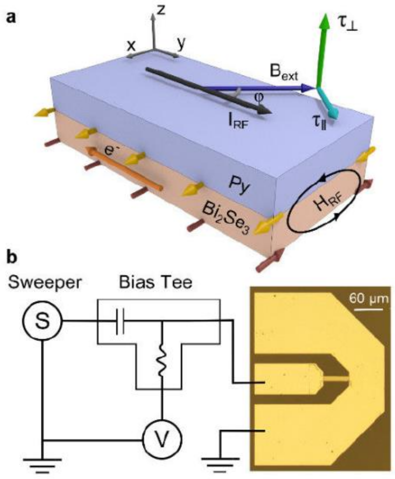
  * Allow self-consistency check (Onsager reciprocity relationship)

  * Eliminate current shunting

  * Isolate TI from FM (CoFeB) influence

Charge-Spin Conversion in TI: Other Methods

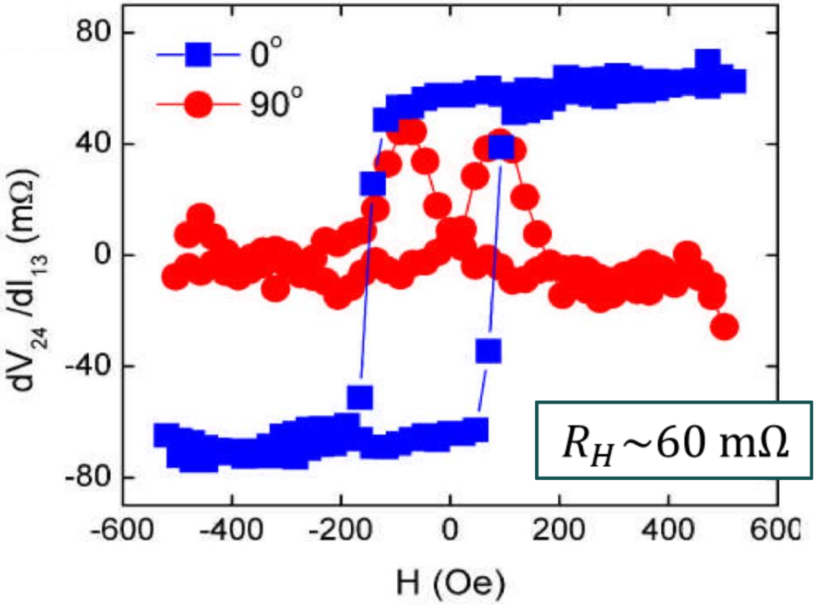
- Potentiometry measurements:
    * Li, Jonker, et al., Nature Nano (2013)
    * Tang, KL Wang et al., Nano Lett (2014)
    * JS Lee, Samarth et al., PRB (2015)
    * Tian, YP Chen et al., Sci Rep (2015)
- Spin-torque FMR:
    * Mellnik, Ralph et al., Nature (2014)
    * Y. Wang, H. Yang et al., PRL (2015)
- Spin pumping:
    * Shiomi et al., Saitoh et al., PRL (2014)
    * Jamali, JP Wang et al., Nano Lett (2015)
- Spin-torque switching:
    * Fan, KL Wang et al., Nature Mat (2014),
    * Fan, KL Wang et al., Nature Nano (2016)



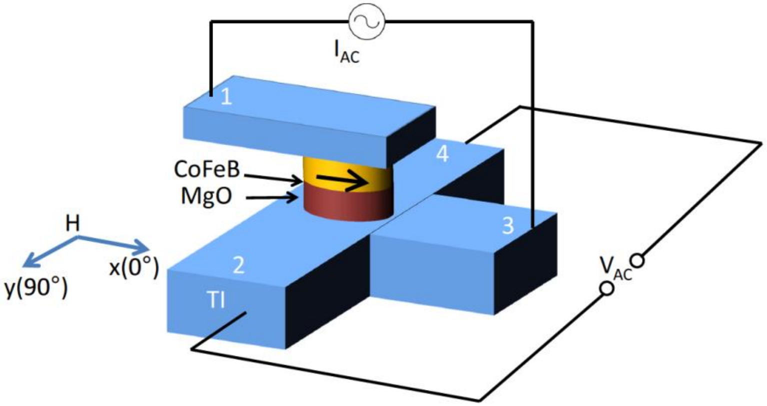
Nature **511**, 449 (2014)
Ralph group

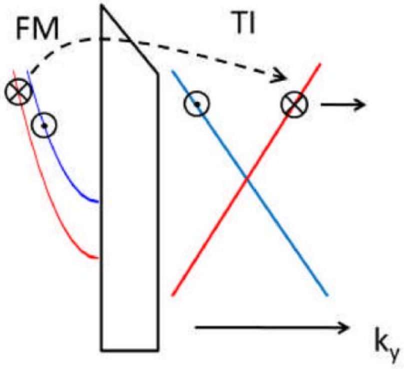
Spin-Polarized Tunneling in Bi_2Se_3: Zero Bias

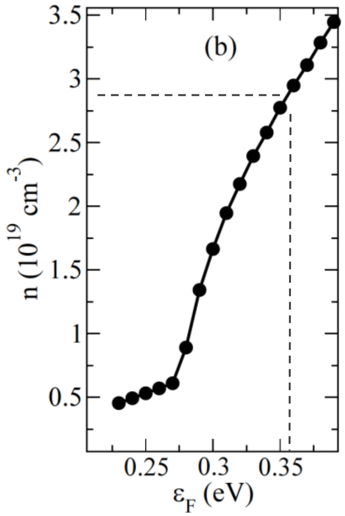
- Tunneling configuration



$R_H \sim 60\ \text{m}\Omega$





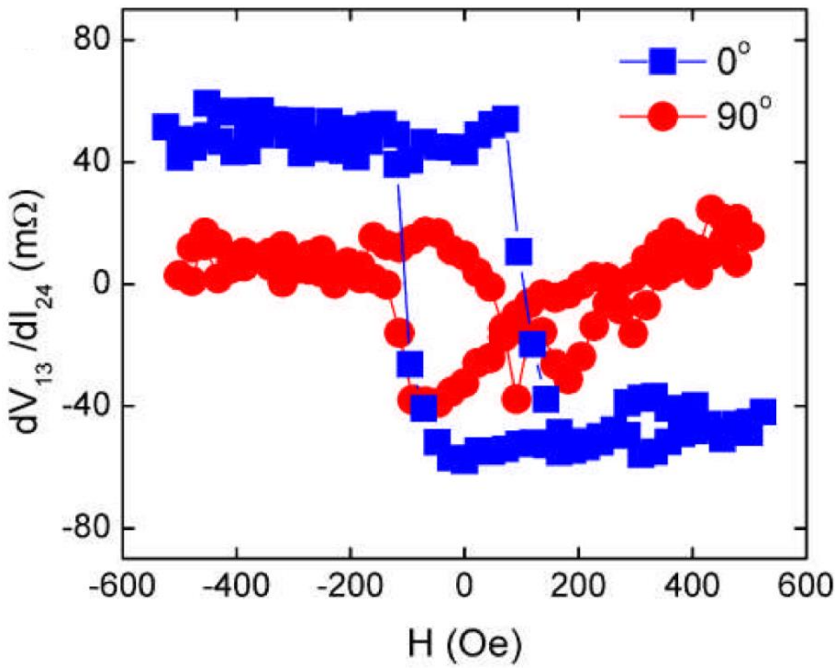


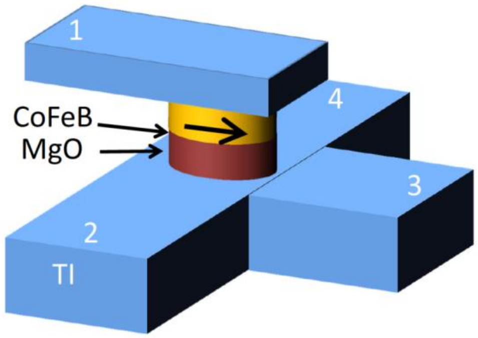
$$\boxed{\frac{dV}{dI} = \eta P_{TI} P_J R_{\square} \frac{v_F \tau_{sf}}{w} \approx \eta P_{TI} P_J R_{\square} \frac{l}{w}}$$

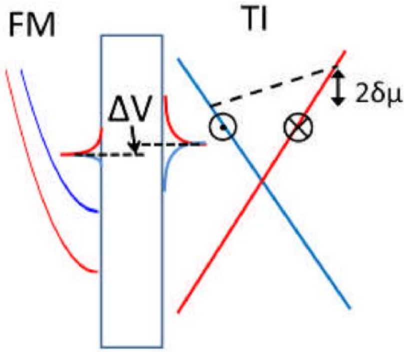
$$\eta P_{TI} = (0.01 - 0.1) \times 0.4$$

Potentiometry Measurement in Bi_2Se_3: Zero Bias

- Potentiometry configuration (Edelstein effect)







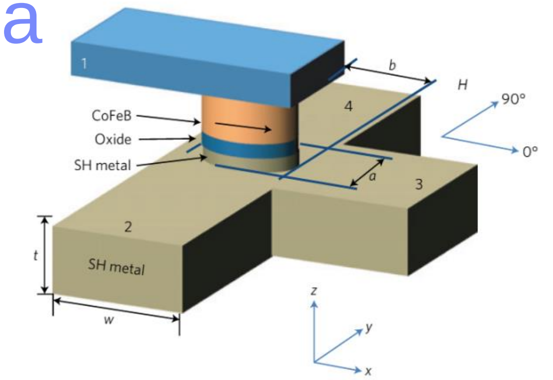
Onsager relation $$\frac{dV}{dI} \approx \eta P_{TI} P_J R_\square \frac{l}{w}$$

$$\eta P_{TI} = (0.01 - 0.1) \times 0.4$$

$$\frac{dV_{24}}{dI_{13}} = \frac{\theta_{SH} P \rho}{w} \cdot \frac{\lambda_{sf}}{t} \cdot \tanh(t/2\lambda_{sf})$$

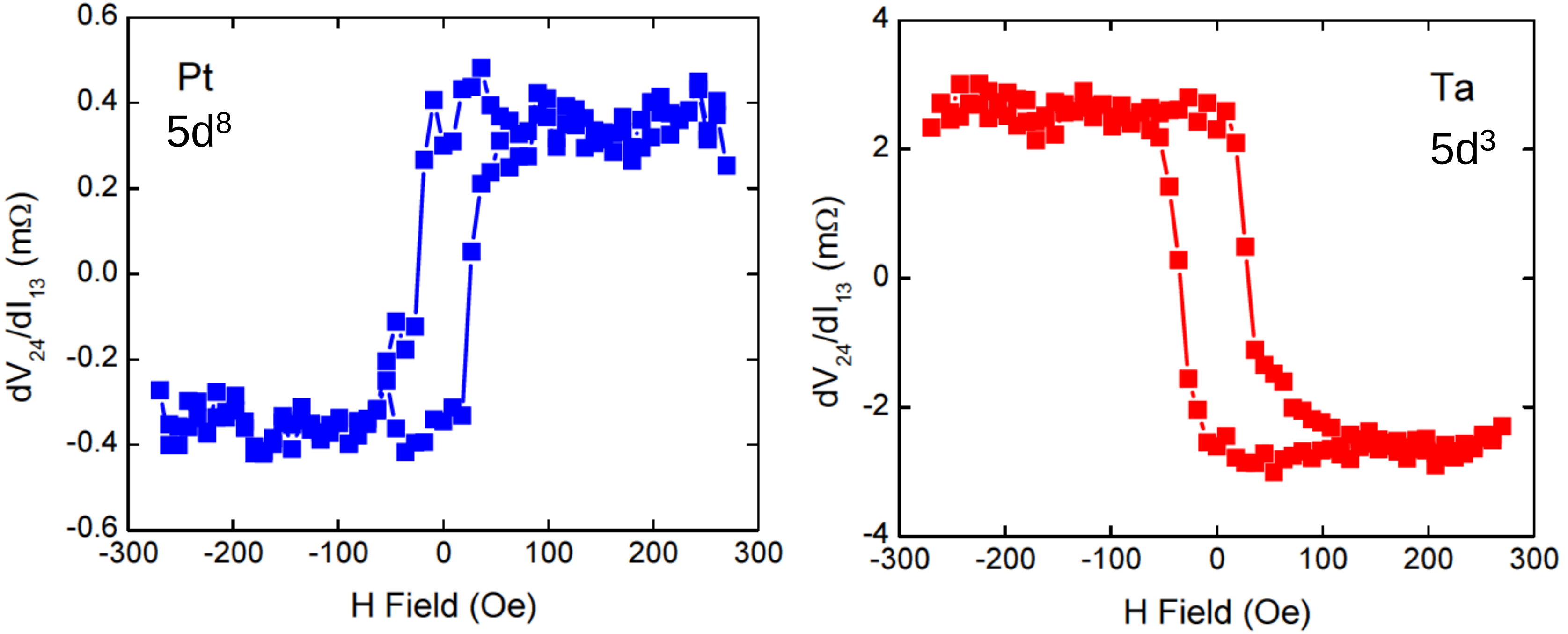
θ_{SH} ~ 0.8 assuming λ_{sf} ~ 1*nm*

Spin-Polarized Tunneling Data: Pt & Ta



$$|\theta_{SH}(\mathrm{Pt})| = 0.04 - 0.09$$

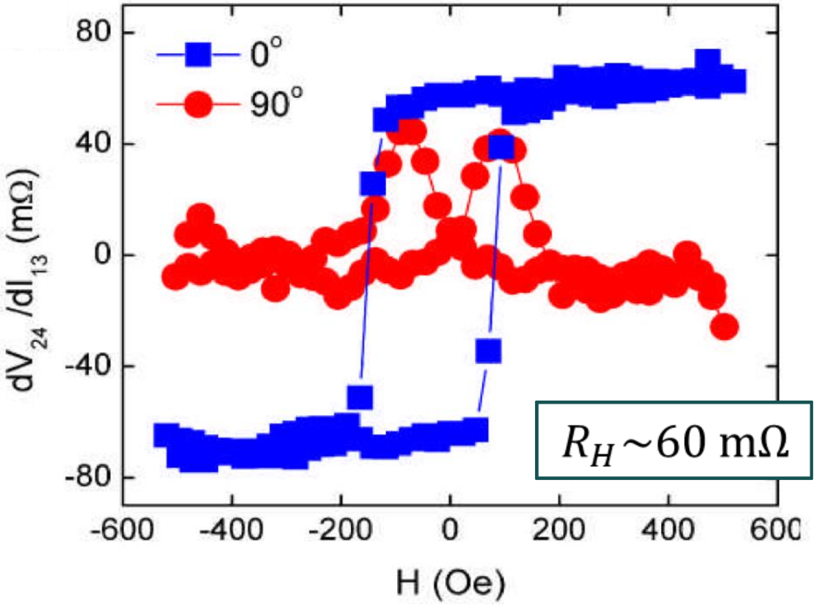
$$|\theta_{SH}(\mathrm{Ta})| = 0.05 - 0.11$$

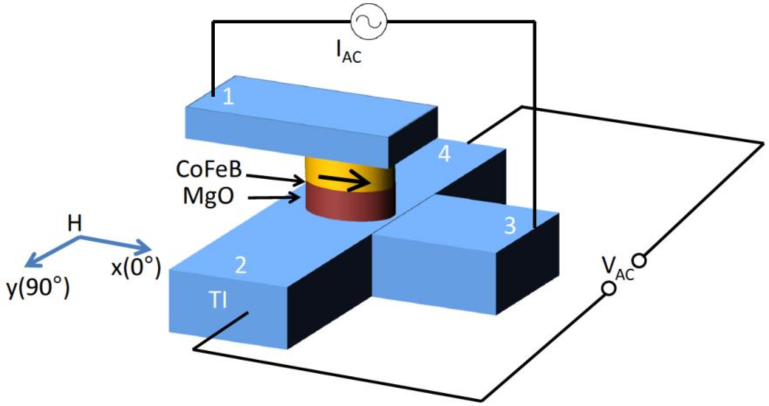


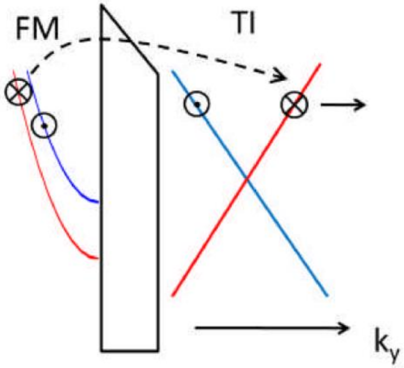
Liu, Chen, & Sun, Nature Phys. 10, 561 (2014)

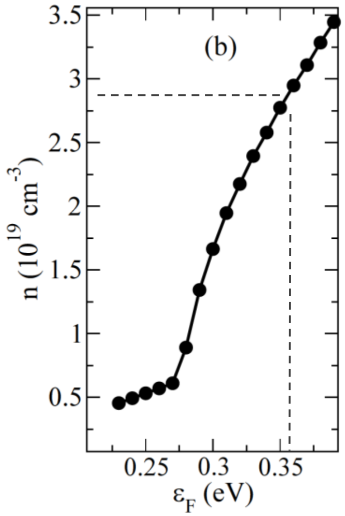
Spin-Polarized Tunneling in Bi_2Se_3: Zero Bias

- Tunneling configuration









$$\frac{dV}{dI} = \eta P_{TI} P_J R_\square \frac{v_F \tau_{sf}}{w} \approx \eta P_{TI} P_J R_\square \frac{l}{w}$$

$\eta P_{TI} = (0.01 - 0.1) \times 0.4$

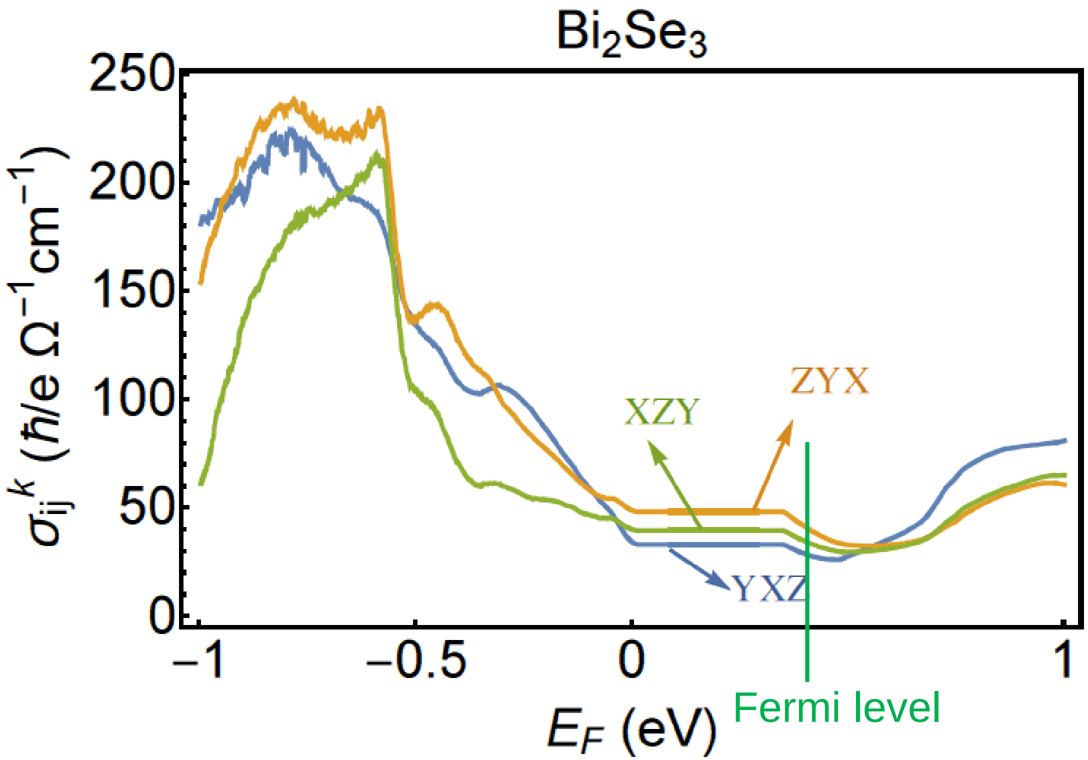
θ_{SH} ~ 0.8 assuming λ_{sf} ~ 1*nm*

$R_\square \sim 1k\Omega$, $P_J \sim 0.5$, $P_{TI} \sim 0.4$,
$w = 8\mu m$, $l = 20 - 130nm$

$$\frac{dV_{24}}{dI_{13}} = \frac{\theta_{SH} P \rho}{w} \cdot \frac{\lambda_{sf}}{t} \cdot \tanh(t/2\lambda_{sf})$$

Surface State vs. Bulk State Contribution in Bi_2Se_3

- Bulk SHE: realistic bandstructure (credit: Flatte, Sahin)



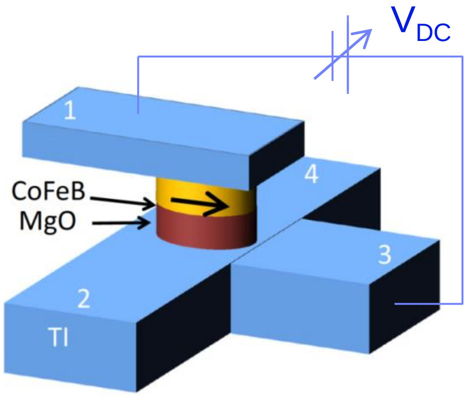
Fermi level

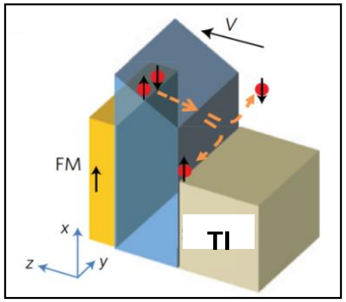
Experiment: $\boxed{\sigma_{Bi_2Se_3}{}^{(SHC)} \sim (0.40 - 1.37) \times 10^3 (\Omega \cdot cm)^{-1} \text{ assuming } \lambda_{sf} = (1-10)\, nm}$

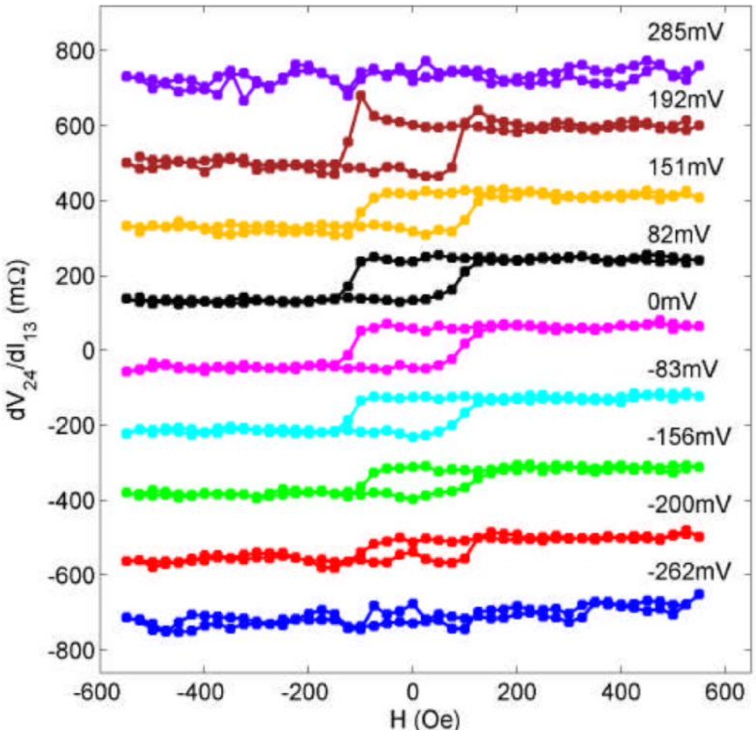
1-2 orders of magnitude larger than theoretical bulk SHE value

Spin-Polarized Tunneling in Bi_2Se_3: Finite Bias

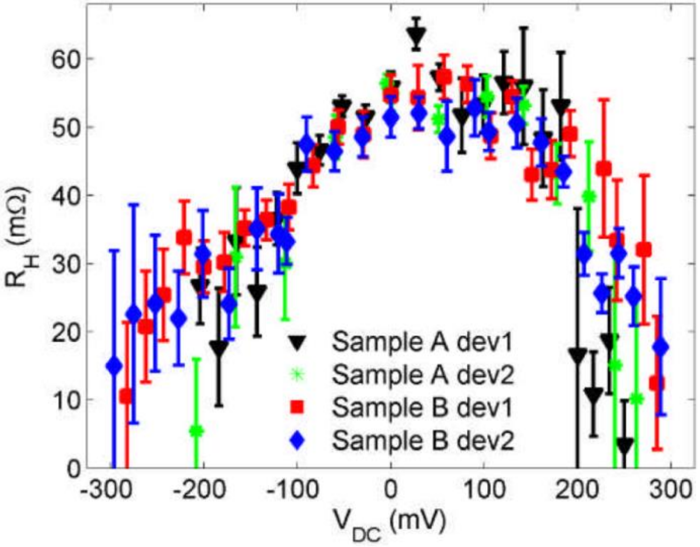
- Energy dependence



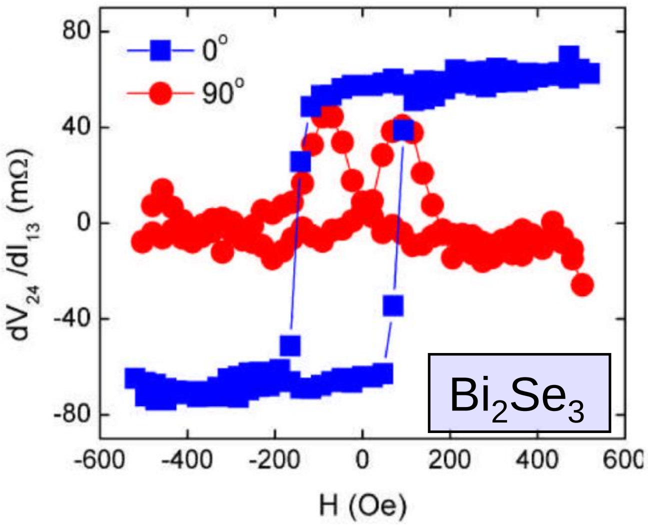


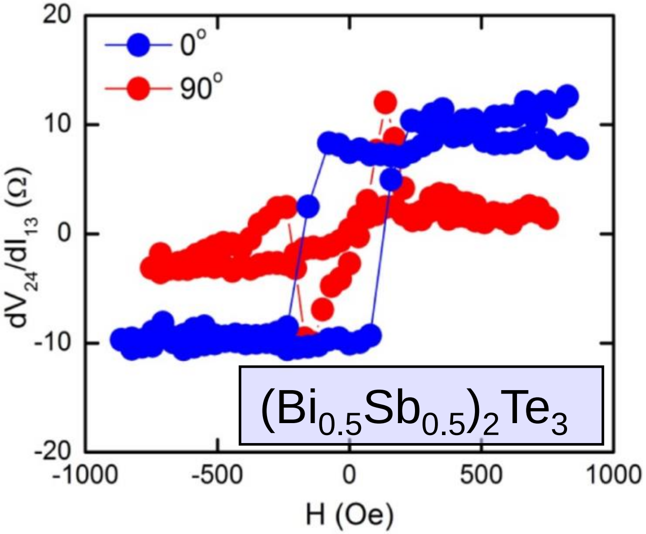


Liu et al., Phys. Rev. B 91, 235437 (2015)



Optimizing Charge-Spin Conversion via Surface State





R_H (Bi_2Se_3) $\sim 60\ m\Omega$ **vs.** R_H ($(Bi_{0.5}Sb_{0.5})_2Te_3$) $\sim 9\ \Omega$

$$\frac{dV}{dI} \approx \eta P_{TI} P_J R_{\square} \frac{l}{w}$$

η (Bi_2Se_3) $\sim (0.01 - 0.1)$ **vs.** η ($(Bi_{0.5}Sb_{0.5})_2Te_3$) $\sim (0.6 \pm 0.2)$

$$\frac{dV}{dI} \approx \frac{\theta_{SH} P_J \rho}{w} \cdot \frac{\lambda_{sf}}{t} \cdot \tanh(t/2\lambda_{sf})$$

Clearly surface-state spin-momentum locking effect

θ_{SH} (Bi_2Se_3) ~ 0.8 **vs.** θ_{SH} ($(Bi_{0.5}Sb_{0.5})_2Te_3$) $\sim (20 \pm 5)$!

Summary A

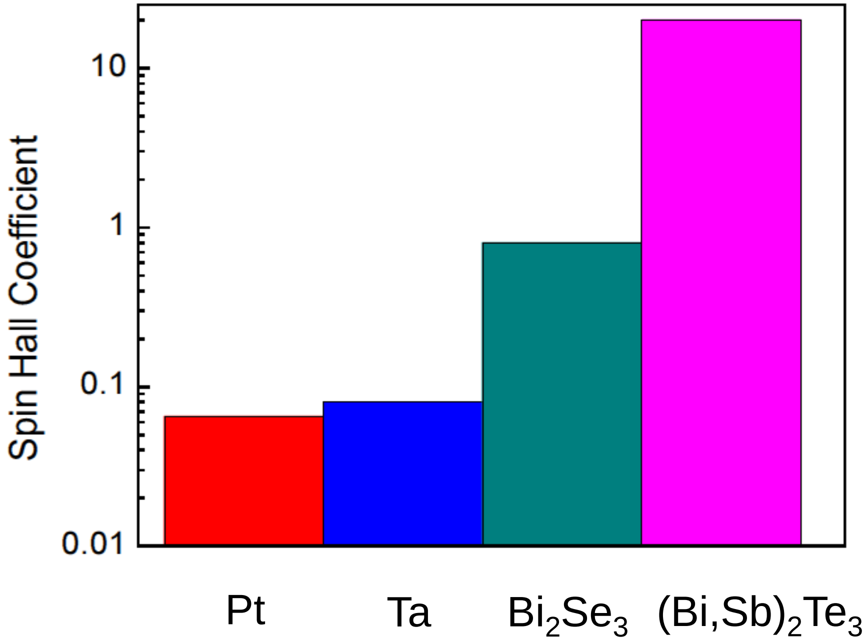
- Spin-polarized tunneling study on Bi_2Se_3 and $(Bi_{0.5}Sb_{0.5})_2Te_3$

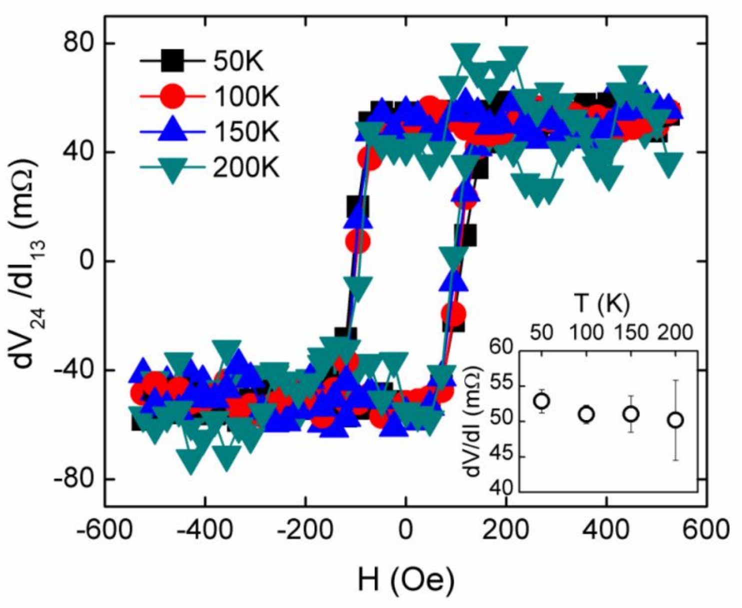
  * Record-high charge-spin conversion observed in TI

  * Surface-state origin: spin-momentum locking

  * energy dependence information

  * RT promising



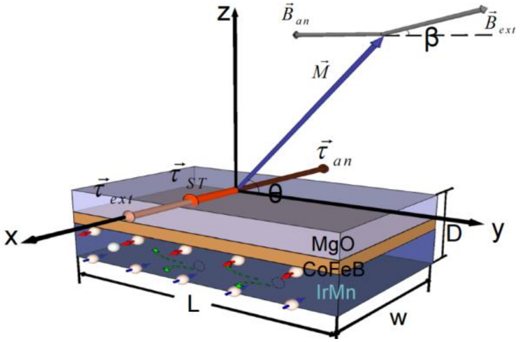


Liu et al., Phys. Rev. B 91, 235437 (2015)

Liu, Chen, & Sun, Nat. Phys. **10**, 561 (2014)

Potential Applications

- Spin-orbit-torque MRAM and spin logic using TI?



PRL **109**, 096602 (2012)

Q: Is technologically relevant PMA/TI practical for MRAM?

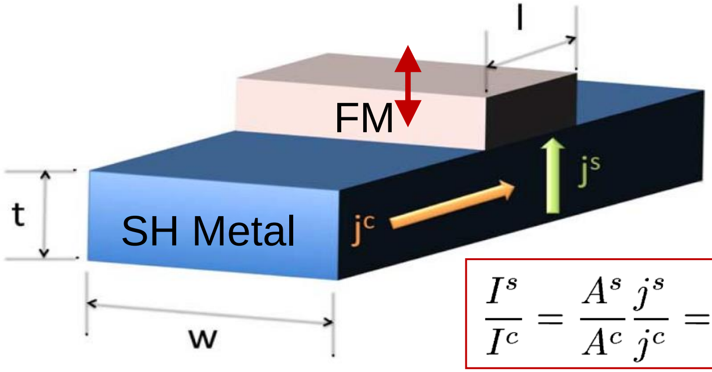
1. STT in PMA-MTJ: overcome damping torque

$$\alpha\hat{m}\times\left(\vec{m}\times\vec{B}_{eff}\right)$$

$$B_{eff}\,(\mu d\theta)\sin\theta = B_{ani}\,\mu\cos\theta\sin\theta d\theta$$

$$B_{eff} = B_{ani}\cos\theta$$

α_{CoFeB} ~ 0.4%



$$\frac{I^s}{I^c} = \frac{A^s}{A^c}\frac{j^s}{j^c} = \frac{l}{t}\Theta_{SH}$$

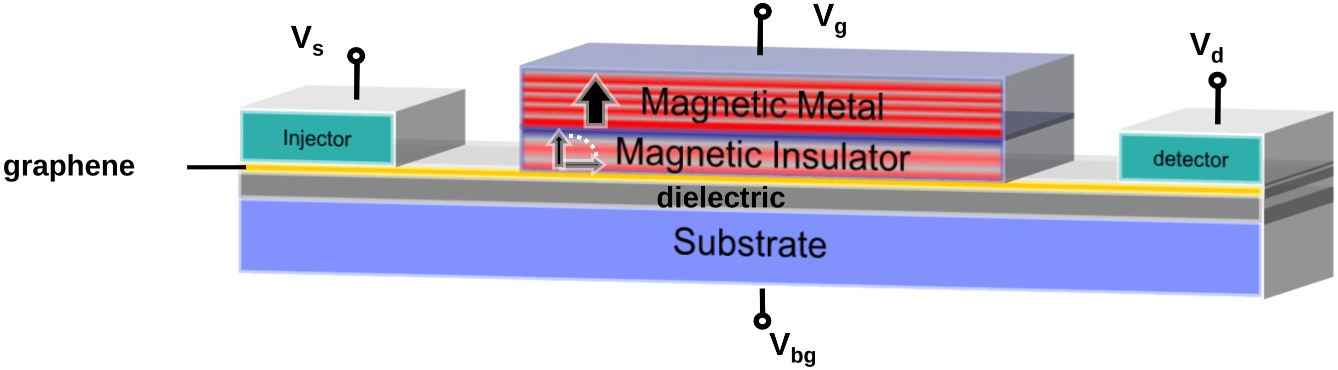
Hoffmann IEEE Trans Mag (2013)

2. SOT in SH-PMA bilayer: overcome anisotropy torque → large!

$$\vec{\tau}_{an} = -\hat{m}\times\vec{B}_{an}$$

Graphene Spintronics & Exchange Field

- **Spin transport**: small spin-orbit coupling, long spin relaxation length (≥ μm)
- **Spin generation:** spin injection and Zeeman spin-Hall effect



- **2D**: classical and quantum effects (e.g. QHE, QSHE, QAHE)
- **2D**: spin control by Rashba or Exchange Field (10 – 100 Tesla)

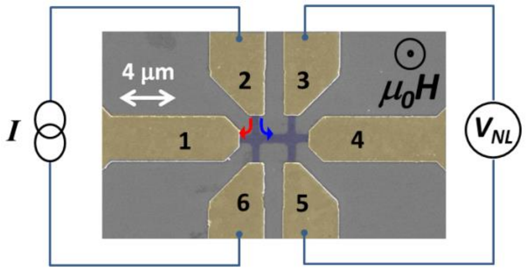
Graphene/Magnetic-Insulator: Exchange Field

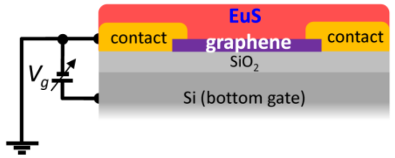
- Graphene/EuS as model system: in-situ deposition
  - Much better controlled stoichiometry (direct evaporation of target materials)
  - EuS wide band-gap insulator (1.65 eV), no current shunting
  - Large exchange splitting in bulk conduction band, ~0.36 eV

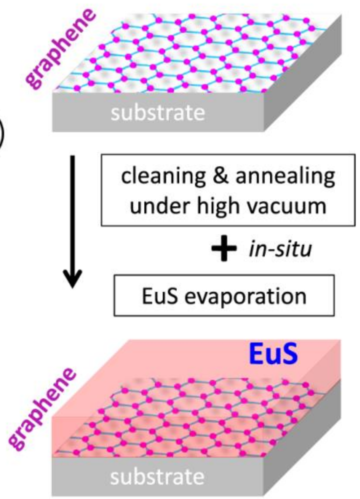
    (c.f. Busch, Junod, and Wachter, Phys. Lett. 12, 11 (1964))
  - Large magnetic moment per Eu ion, $\langle S_z \rangle \sim 7\mu_B$
  - Expect large exchange splitting, $\Delta \propto J\langle S_z \rangle$
  - EuS demonstrated to spin-polarize quasiparticles in Al and Bi_2Se_3

P. Wei, et al., Nature Materials (2016) doi:10.1038/nmat4603

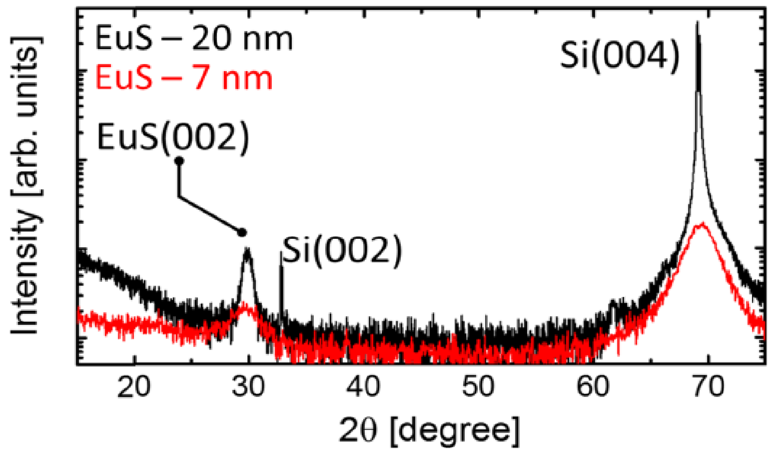
CVD Graphene/EuS Heterostructure: *Raman, XRD, TEM*

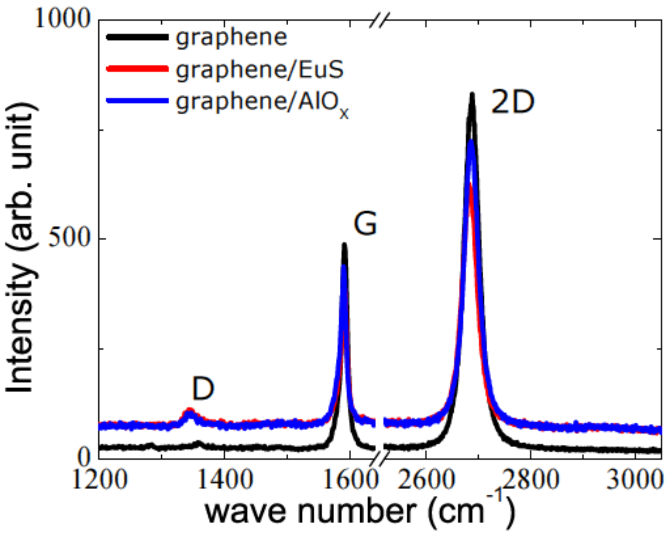




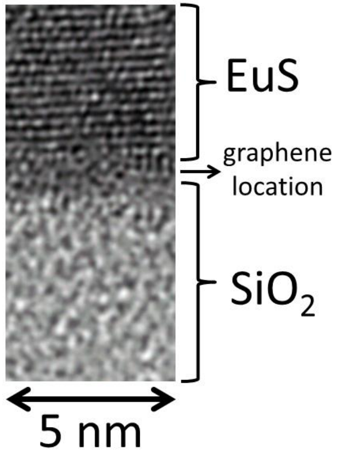


- X-ray diffraction (XRD):
  high quality single phase growth of EuS





- Hall-bar devices: *fabrication simple*
- EuS deposition at final step, capped with AlO_x:
  EuS properties preserved
- Raman spectra:
  graphene structure intact
- Transmission electron microscopy:
  clean interface



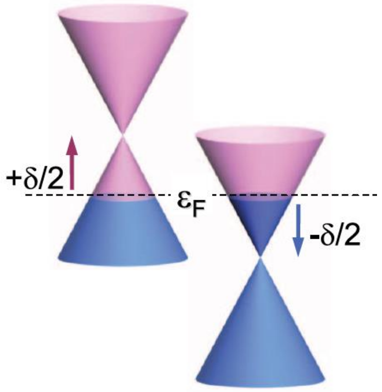
Electrical Detection of Interfacial Exchange Field:

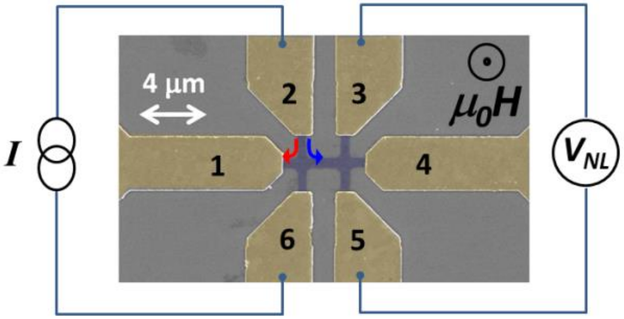
Zeeman spin-Hall effect & nonlocal transport

- Applied field (*μ₀H*) + exchange field (B_{exc}) = total Zeeman field (B_Z)

→ spin splitting (E_Z)

→ spin-polarized electron vs. hole-like carriers near Dirac point





$$R_{nl,D} \propto \frac{1}{\rho_{xx}}\left(E_Z \frac{\partial \rho_{xy}}{\partial \mu}\right)^2\Bigg|_{\mu_D}$$

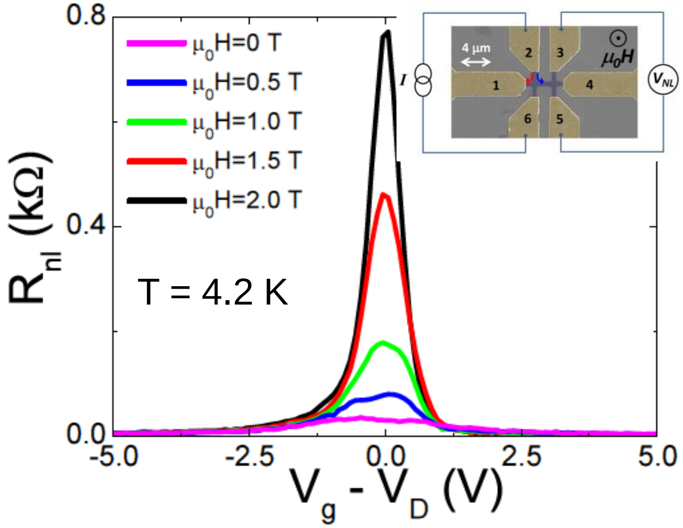
Abanin et al. Science (2011)
Abanin et al. PRL (2011)

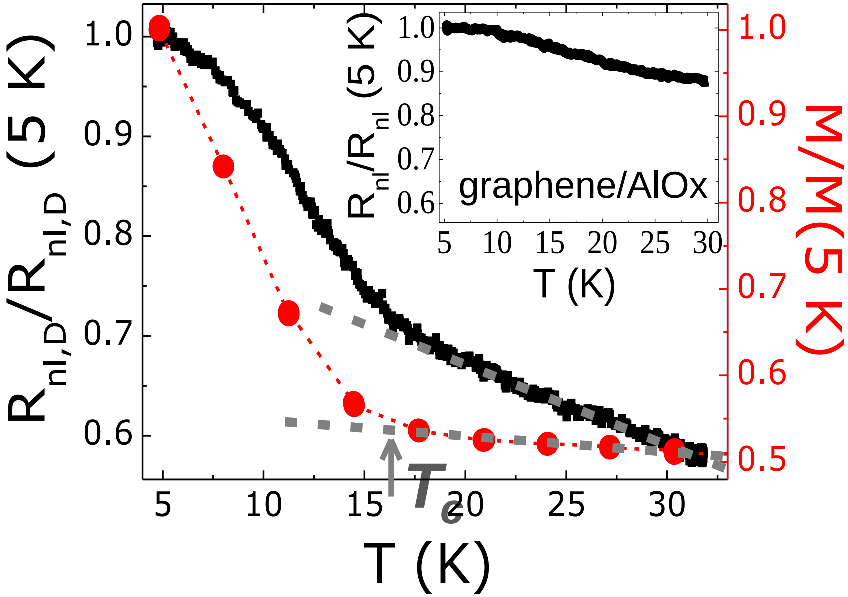
- $\mu_0 H$ (⊥) couples to orbital motion:

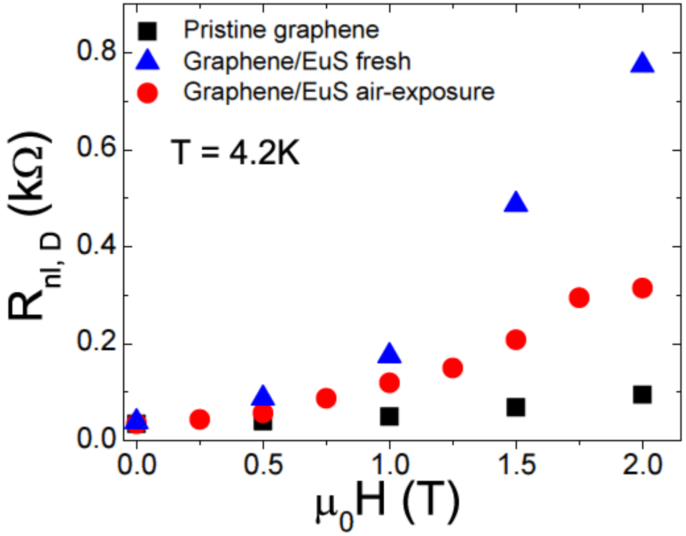
→ transverse spin current (Zeeman spin Hall effect)

→ inverse spin-Hall-like effect → nonlocal voltage/resistance ($R_{nl,D} \equiv V_{nl,D}/I$)

Zeeman Spin-Hall Effect: *EuS induced enhancement*







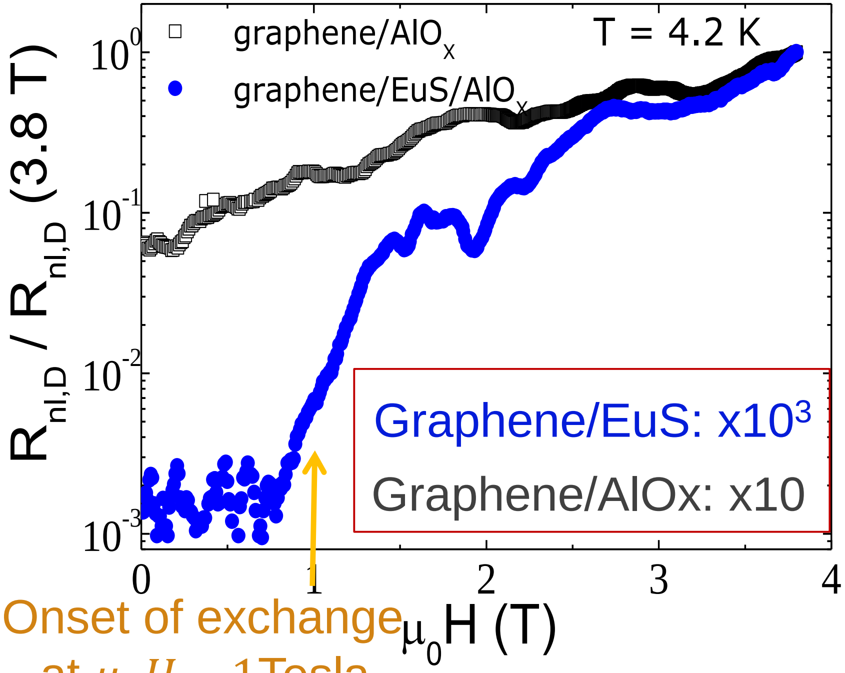
Magnetic origin of $R_{nl,D}$

- Enhancement of R_{nl} signal by EuS deposition
- Reduction of R_{nl} signal upon EuS oxidation
- R_{nl} correlates with M(T)

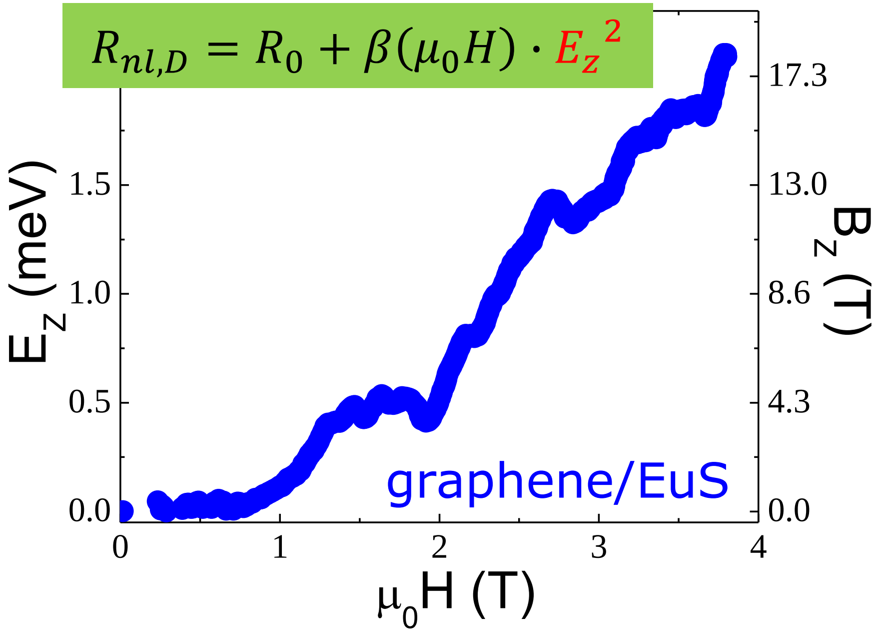
$$R_{nl,D} \propto \frac{1}{\rho_{xx}}\left(E_Z \frac{\partial \rho_{xy}}{\partial \mu}\right)^2\Bigg|_{\mu_D}$$

EuS Induced Interfacial Exchange Field

- Quantifying the EuS induced exchange field



Onset of exchange at $\mu_0 H_0 \sim 1$Tesla



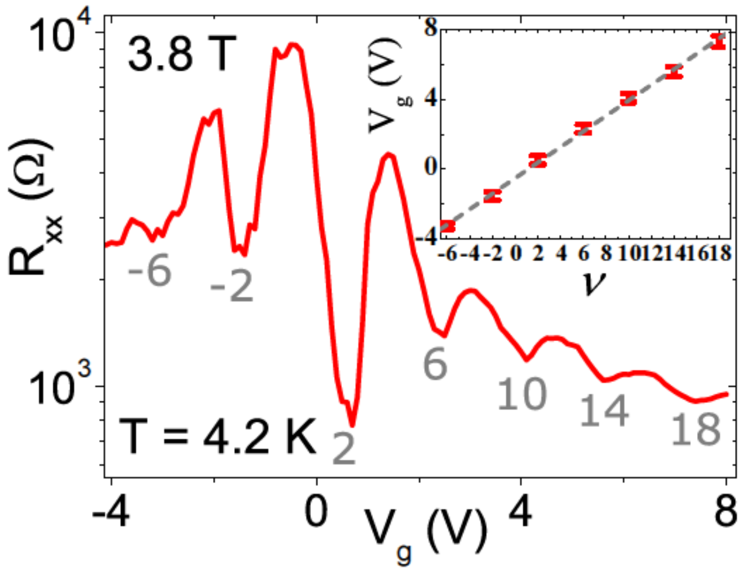
$$R_{nl,D} = R_0 + \beta(\mu_0 H) \cdot E_Z{}^2$$

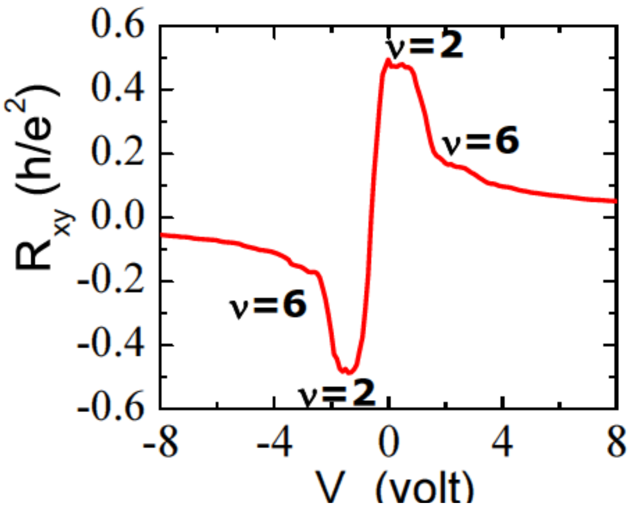
When $\mu_0 H$ = 3.5T, B_Z >15 T

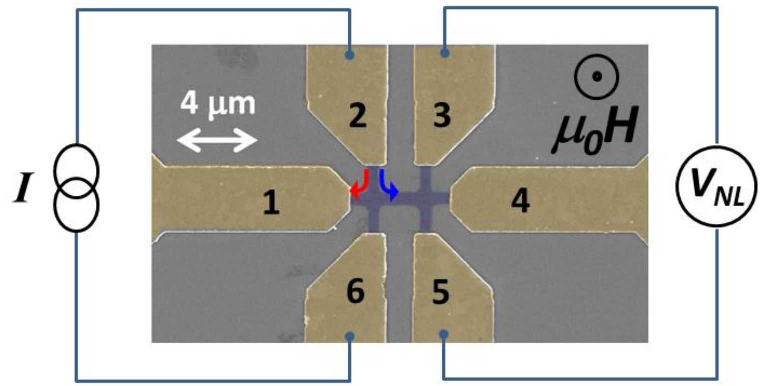
E_Z and B_Z are **lower-bound estimates** because:

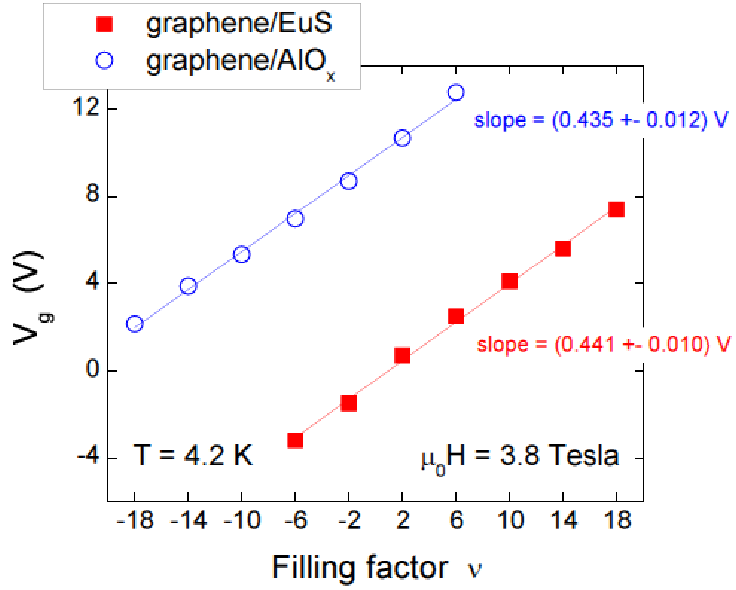
- We assume E_Z contributed only by $\mu_0 H$ at onset
- $\frac{\beta(\mu_0 H)}{\beta(\mu_0 H_0)}$ depends on mobility and is smaller in graphene/EuS (<10% correction)

Graphene/EuS: *Quantum Hall regime*



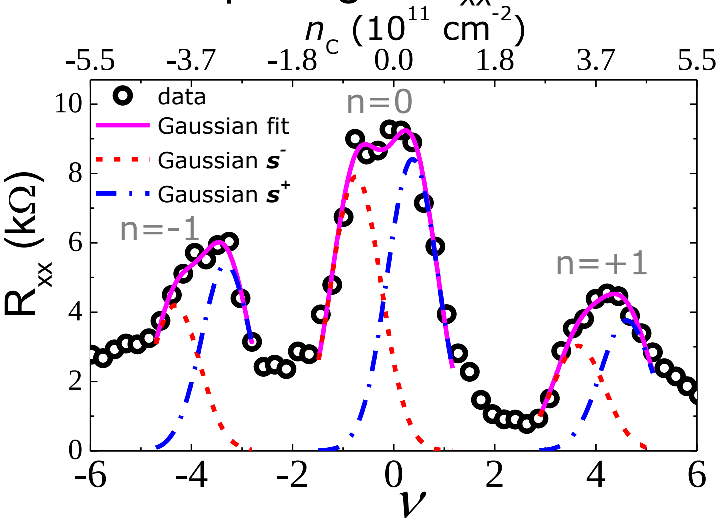




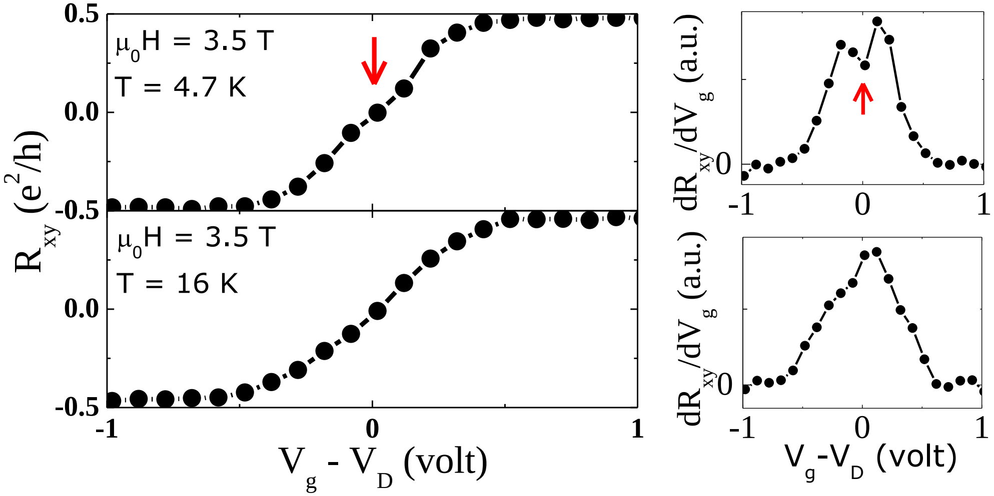


Quantum Effect: *Landau Level (LL) Splitting*

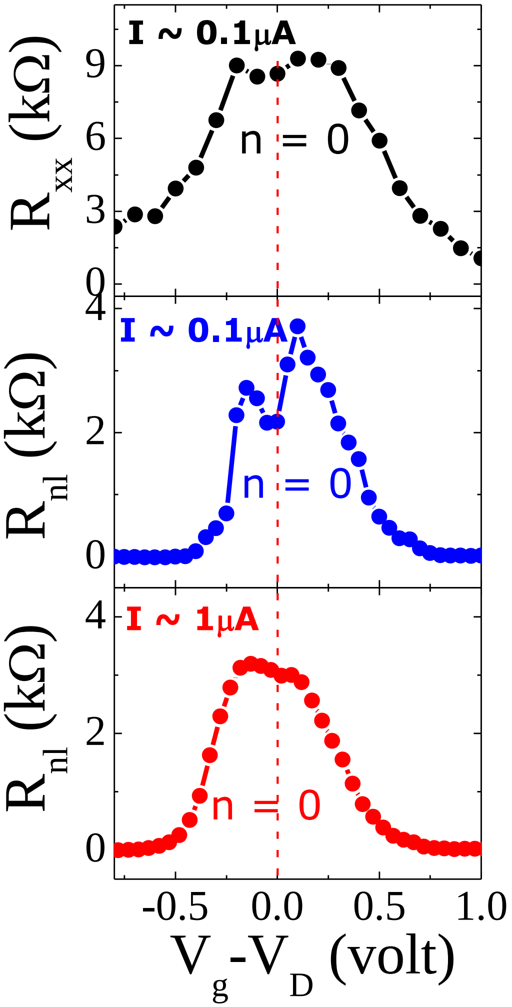
- $\nu = 0$ LL splitting in R_{xx} :



- New R_{xy} plateau at n = 0 :

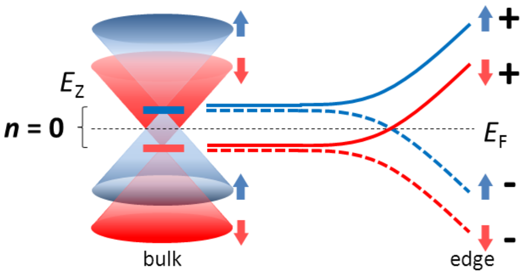


- $\nu = 0$ LL splitting in R_{nl} :



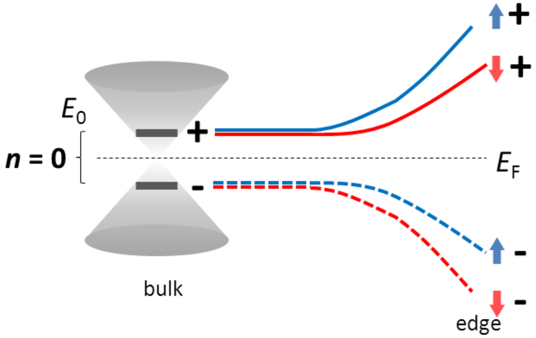
Quantum Effect: *Spin-Polarized Chiral Edge States*

Graphene/EuS

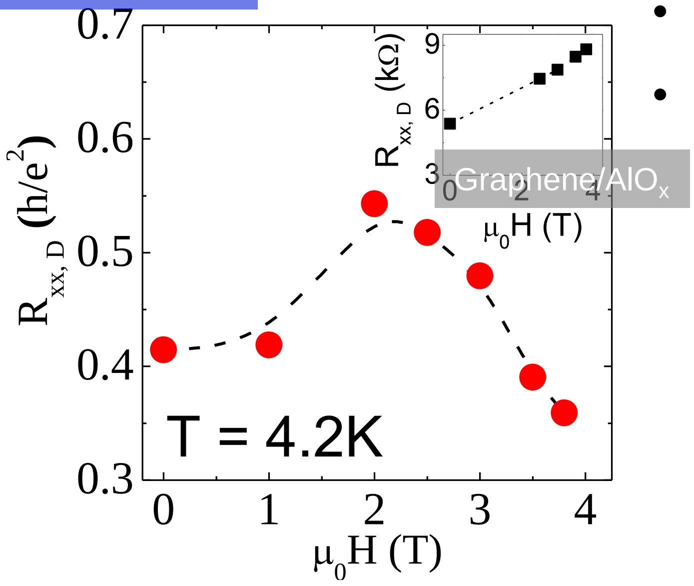


D. Abanin et al., PRL (2006)

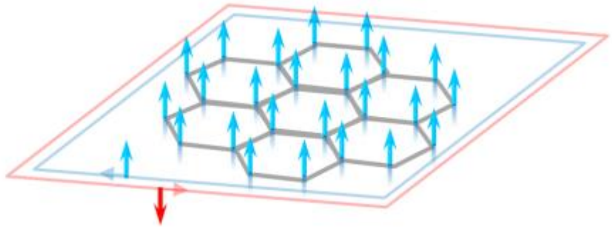
Graphene/AlO_x



Graphene/EuS



- Unique regime: Zeeman >> orbital field ($\mu_0 H$)
- Chiral spin edge modes → gapless modes



Summary B: Graphene/EuS Exchange Field

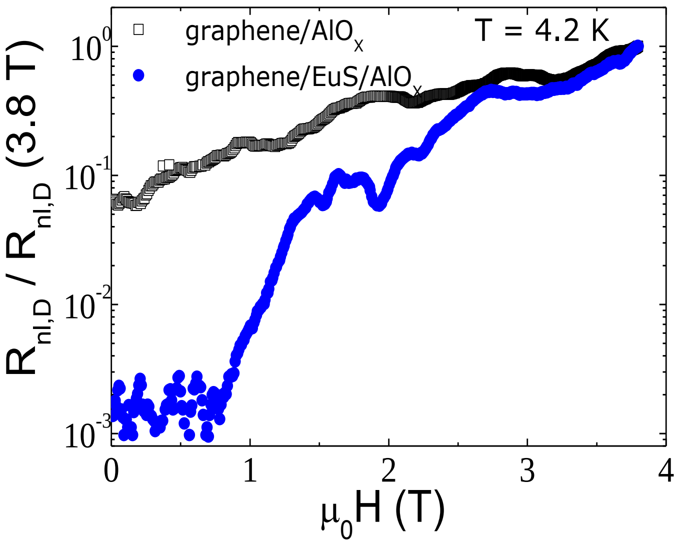
- Electrical detection via Zeeman SHE

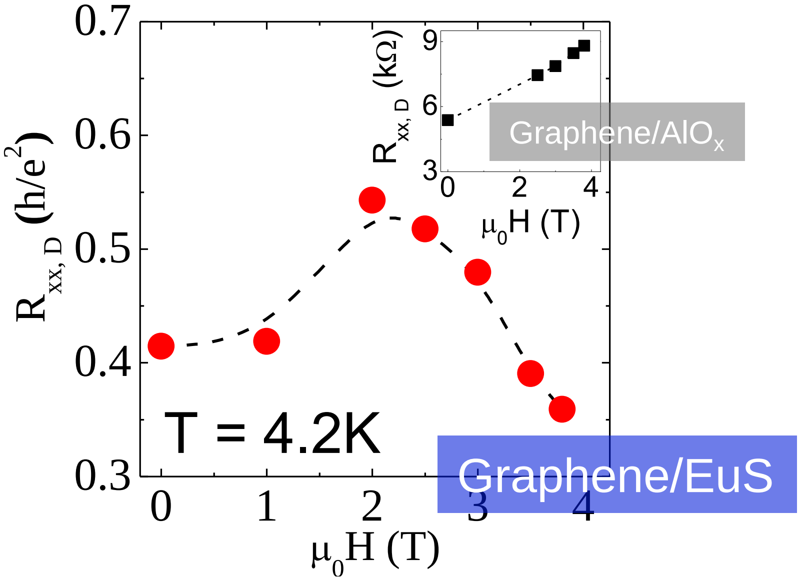
  * Orders of magnitude enhancement in ZSHE R_{nl}

  * $R_{nl}(T)$ correlates with $M(T)$: magnetic origin

  * Giant B_Z (> 15T) when EuS nearly polarized (spin control)

  * Observed unusual chiral spin edge modes in low field





P. Wei, et al., Nature Mat. (2016), doi:10.1038/nmat4603. arXiv: 1510.05920