Physics in Quasi-2D Materials for Spintronics Applications

Topological Insulators and Graphene

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Spintronics

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)


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)

Spin-Orbit Coupling for Spin Generation

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

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

Hoffmann IEEE Trans Mag (2013)
Charge-Spin Conversion in TI: Spin-Polarized Tunneling

- 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:
  * JS Lee, Samarth et al., PRB (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)

• Spin-torque switching:
  * Fan, KL Wang et al., Nature Mat (2014),
Spin-Polarized Tunneling in Bi$_2$Se$_3$: Zero Bias

- Tunneling configuration

\[
\frac{dV}{dl} = \eta P_{TI} P J R_{\square} \frac{v_F \tau_{sf}}{w} \approx \eta P_{TI} P J R_{\square} \frac{l}{w}
\]

\[\eta P_{TI} = (0.01 - 0.1) \times 0.4\]
Potentiometry Measurement in Bi$_2$Se$_3$: Zero Bias

- Potentiometry configuration (Edelstein effect)

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

Onsager relation
\[
\frac{dV}{dl} \approx \eta P_{TI} P_f R_\square \frac{l}{W}
\]

\[
\frac{dV_{24}}{dI_{13}} = \frac{\theta_{SH} P \rho}{w} \frac{\lambda_{sf}}{t} \tanh\left(t/2\lambda_{sf}\right)
\]

\[\theta_{SH} \sim 0.8 \text{ assuming } \lambda_{sf} \sim 1 \text{nm}\]
Spin-Polarized Tunneling Data: Pt & Ta

\[ |\theta_{SH}(Pt)| = 0.04 - 0.09 \]
\[ |\theta_{SH}(Ta)| = 0.05 - 0.11 \]

Spin-Polarized Tunneling in Bi$_2$Se$_3$: Zero Bias

- **Tunneling configuration**

\[ \frac{dV}{dl} = \eta P_{TI} P_j R_\Box \frac{\nu_F \tau_{sf}}{w} \approx \eta P_{TI} P_j R_\Box \frac{l}{w} \]

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

\[ \theta_{SH} \sim 0.8 \text{ assuming } \lambda_{sf} \sim 1 \text{ nm} \]

\[ R_\Box \sim 1k\Omega, \quad P_j \sim 0.5, \quad P_{TI} \sim 0.4, \quad w = 8\mu m, \quad l = 20 - 130nm \]

\[ \frac{dV_{24}}{dl_{13}} = \frac{\theta_{SI} P_j \lambda_d}{w} \cdot \tanh\left(\frac{t}{2\lambda_d}\right) \]
Surface State vs. Bulk State Contribution in Bi$_2$Se$_3$

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

Experiment:

$$\sigma_{Bi_2Se_3}^{(SHC)} \sim (0.40 - 1.37) \times 10^3 (\Omega \cdot cm)^{-1}$$

assuming $\lambda_{sf} = (1 - 10) \text{ nm}$

1-2 orders of magnitude larger than theoretical bulk SHE value
Spin-Polarized Tunneling in Bi$_2$Se$_3$: Finite Bias

- Energy dependence

Optimizing Charge-Spin Conversion via Surface State

\[ R_H (\text{Bi}_2\text{Se}_3) \sim 60 \, \text{m}\Omega \quad \text{VS.} \quad R_H ((\text{Bi}_{0.5}\text{Sb}_{0.5})_2\text{Te}_3) \sim 9 \, \Omega \]

\[ \frac{dV}{dl} \approx \eta P_T P_J R_{\square} \frac{l}{w} \]

\[ \eta (\text{Bi}_2\text{Se}_3) \sim (0.01 - 0.1) \quad \text{VS.} \quad \eta ((\text{Bi}_{0.5}\text{Sb}_{0.5})_2\text{Te}_3) \sim (0.6 \pm 0.2) \]

\[ \frac{dV}{dl} \approx \frac{\theta_{SH} P_J \rho}{w} \cdot \frac{\lambda_{sf}}{t} \cdot \tanh \left( \frac{t}{2\lambda_{sf}} \right) \]

\[ \theta_{SH} (\text{Bi}_2\text{Se}_3) \sim 0.8 \quad \text{VS.} \quad \theta_{SH} ((\text{Bi}_{0.5}\text{Sb}_{0.5})_2\text{Te}_3) \sim (20 \pm 5)! \]

Clearly surface-state spin-momentum locking effect
Summary A

- Spin-polarized tunneling study on Bi$_2$Se$_3$ and (Bi$_{0.5}$Sb$_{0.5}$)$_2$Te$_3$

  * Record-high charge-spin conversion observed in TI
  * Surface-state origin: spin-momentum locking
  * Energy dependence information
  * RT promising

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

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

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

1. STT in PMA-MTJ:
   - overcome damping torque
   \[
   \alpha \hat{m} \times \left( \hat{m} \times \vec{B}_{\text{eff}} \right) = B_{\text{eff}} \mu d \theta \sin \theta = B_{\text{ani}} \mu \cos \theta \sin \theta d \theta
   \]
   \[
   B_{\text{eff}} = B_{\text{ani}} \cos \theta
   \]
   \[
   \alpha_{\text{CoFeB}} \approx 0.4\%
   \]

2. SOT in SH-PMA bilayer:
   - overcome anisotropy torque \( \rightarrow \) large!
   \[
   \hat{\tau}_{\text{an}} = -\hat{m} \times \vec{B}_{\text{an}}
   \]

Hoffmann IEEE Trans Mag (2013)
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\(_2\)Se\(_3\)

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

- X-ray diffraction (XRD): *high quality single phase growth of EuS*
- Transmission electron microscopy: clean interface
- Raman spectra: graphene structure intact
- Hall-bar devices: *fabrication simple*
- EuS deposition at final step, capped with AlO$_x$: *EuS properties preserved*
- Transmission electron microscopy: *clean interface*
Electrical Detection of Interfacial Exchange Field:

**Zeeman spin-Hall effect & nonlocal transport**

- Applied field \( (\mu_0 H) \) + exchange field \( (B_{exc}) \) = total Zeeman field \( (B_Z) \)
  - spin splitting \( (E_Z) \)
  - spin-polarized electron vs. hole-like carriers near Dirac point

- \( \mu_0 H \) (\( \perp \)) couples to orbital motion:
  - transverse spin current (Zeeman spin Hall effect)
  - inverse spin-Hall-like effect \( \rightarrow \) nonlocal voltage/resistance \( (R_{nl,D} \equiv V_{nl,D}/I) \)

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Abanin et al. Science (2011)
Abanin et al. PRL (2011)
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 $M(T)$

\[
R_{nl,D} \propto \frac{1}{\rho_{xx}} \left( E_Z \frac{\partial \rho_{xy}}{\partial \mu} \right)^2
\]

$\mu_D$
EuS Induced Interfacial Exchange Field

- Quantifying the EuS induced exchange field

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

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

$R_{xx} (\Omega)$

$R_{xy} (h/e^2)$

$v = 2$

$v = 6$

$\mu_0 H = 3.8 \text{ Tesla}$

slope = $(0.441 \pm 0.010) \text{ V}$

slope = $(0.435 \pm 0.012) \text{ V}$

$T = 4.2 \text{ K}$

$I$ \hspace{1cm} $V_{NL}$

$4 \mu m$ \hspace{1cm} $\mu_0 H$
Quantum Effect: *Landau Level (LL) Splitting*

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

![Graph showing $R_{xx}$ vs $\nu$](image)

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

![Graph showing $R_{xy}$ vs $V_g - V_D$](image)

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

![Graph showing $R_{nl}$ vs $V_g - V_D$](image)
Quantum Effect: Spin-Polarized Chiral Edge States

Graphene/EuS

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