Topological vs. conventional spin torque devices

TI-based devices generate a more efficient spin torque with larger spin torque ratio and lower normalized power consumption compared with heavy metals.

Note difference between Bi$_2$Se$_3$ & (Bi,Sb)$_2$Te$_3$

Han et al., PRL 119 077702 (2017)
Direct spin torque switching in TI/FM devices

Sputtered Bi$_2$Se$_3$ + Ta/CoFeB

θ$_\parallel$ ~ 20
J$_C$ ~ 0.4 MA/cm$^2$

Mahindra et al., Nat. Mater. 18 800 (2018)

MBE: Bi$_{0.9}$Sb$_{0.1}$ + MnGa

θ$_\parallel$ ~ 50
J$_C$ ~ 1.5 MA/cm$^2$

Khang et al., Nat. Mater. 18 808 (2018)
Topological spintronics: so we succeeded?

• Measurements of spin-charge conversion (spin Hall angle) show that this is higher in Bi₂Se₃ (and also (Bi,Sb)₂Te₃, Bi₁₋ₓSbx) compared with heavy metals.

• Measurements of spin torque devices shows that these materials are also more energy efficient (e.g. MIT/Penn State, Minnesota).

• Looks attractive for technology — but have we understood the physics? Are there any holes in the story you just heard?
Topological spintronics: questions

• When a topological insulator surface is interfaced with a ferromagnetic metal, are the spin textured surface states unperturbed? Do they even exist at a TI/FM metal interface? [Zhang et al., Phys. Rev. B 94, 014435 (2016)]

• In all the reported measurements of spin-charge conversion, where is the chemical potential (Fermi energy) located? [In most experiments so far, $E_F$ is the bulk conduction band.]

• When we make bilayer lateral transport devices with a topological insulator and a ferromagnetic metal, where does most of the current flow? [Resistivity of FM metals $\ll$ resistivity of $\text{Bi}_2\text{Se}_3$]
Spin pumping observed at 300 K from a 
**ferrimagnetic insulator** (YIG) into Bi$_2$Se$_3$ 
thin films.

Hailong Wang et al., PRL 117, 076601 (2016).

Spin pumping from FM insulator into Bi$_2$Se$_3$
Spin pumping from FM insulator into $\text{Bi}_2\text{Se}_3$

$\text{Bi}_2\text{Se}_3$ thickness dependence of spin pumping signal from YIG suggests dominant role of interface or surface states. But, we still have bulk conduction…!

Hailong Wang et al., PRL 117, 076601 (2016).
Probing spin pumping as a function of chemical potential

Use (Bi_Sb)_{x_2}Te_{3} either with gating or varying composition.
As grown films have low enough carrier density to allow gating across Dirac point.
Caveat: films grown on YIG with 1QL seed layer of Bi_{2}Se_{3}
Varying composition takes films from p-type (Sb_{2}Te_{3}) to n-type (Bi_{2}Te_{3}).
Spin-charge conversion vs. chemical potential

Chemical potential in YIG/(Bi,Sb)$_2$Te$_3$ bilayers varied through Dirac point using a top gate.

For convenience, focus on:

\[
\frac{j_e}{J_s} = \lambda_{\text{IREE}}
\]

\[
J_s = f(\omega, g_{\uparrow\downarrow}, \Delta H_{pp}, M_s, h_{RF})
\]

\[
\frac{V_{SP}}{R} \propto \frac{j_e}{J_s} = \lambda_{\text{IREE}}
\]

\[
j_e = \frac{V_{SP}}{R_W}
\]
Spin-charge conversion vs. chemical potential

Systematic measurements of spin pumping in YIG/(Bi,Sb)$_2$Te$_3$ bilayers as a function of chemical potential. Chemical potential varied using either gate voltage or sample composition (extrinsic unintentional doping). Spin-to-charge conversion efficiency is independent of chemical potential within surface states.

Hailong Wang et al, submitted
Calculation of spin Hall conductivity in TIs

\[ \sigma_{||} = \frac{e\hbar}{V} \sum_{\vec{k}} \sum_{n} f_{\vec{k}n} \Omega^z_n(\vec{k}) \]

\[ \Omega_n(\vec{k}) = \sum_{n \neq n'} \left| \begin{pmatrix} u_{n\vec{k}} \\ j_y \end{pmatrix} \right| \left| \begin{pmatrix} u_{n'\vec{k}} \\ \hat{v}_x \end{pmatrix} \right| \left( E_{n\vec{k}} - E_{n'\vec{k}} \right)^2 \]

\[ \sigma_{||} = \frac{e\hbar}{V} \int_{-\infty}^{\infty} f(\epsilon) \rho_{DOC}(\epsilon) d\epsilon \]

Spin Hall conductivity calculated using bulk states in Bi\textsubscript{1-x}Sb\textsubscript{x} (strong TI for 0.07 < x < 0.22)

Kubo formula relates \( \sigma_{||} \) to ‘density of Berry curvature.’

Bulk-edge correspondence: spin-orbit coupling of bulk states yields same \( \sigma_{||} \) as surface states.
Spin-charge conversion vs. chemical potential

Do only surface states matter? New experiments + theory indicate that the answer is more subtle & deeper...

‘Bulk-surface correspondence’ suggests that bulk states & surface states both contribute to spin Hall conductivity
Spin-charge conversion variation with $E_F$: an alternate picture

**Recent results reported by other groups:**

- Spin Seebeck
- Spin torque FMR
- Spin-polarized tunneling

Nature Comm. 7, 11458 (2016)

J. Shi (UC Riverside)

$(\text{Bi,Sb})_2\text{Te}_3 + \text{YIG}$

Nature Physics (2016) doi:10.1038/nphys3833

Otani (Tokyo)
A unique topological spintronic device proposal

- Spin-charge conversion at topological insulator/ferromagnetic insulator interfaces for a “voltage-driven topological spin switch”
- Relies on the “global” effects of spin-orbit coupling in entire topological insulator band structure, not just surface states.

A ‘synthetic multiferroic’ for spin-based logic or memory that uses strong SO coupling in insulating bulk of TI.

Flatte, AIP Advances 7, 055923 (2017)
VTSS: Predicted Performance

Assuming a switching voltage of 50 mV ⇒ 100 GHz switching rate & 10 meV switching energy: energy-delay product ≈ $3 \times 10^{-32}$ J.s.

$$\frac{dn_{\text{spins}}}{dt} = \frac{\sigma_{\text{SHC}} V_{\text{switch}}}{\hbar/2 L} = \frac{200 \text{THz}}{\text{nm}^2} \frac{V_{\text{switch}}}{\text{Volts}}$$

$$\nu_{\text{switch}} = 600 \text{GHz} \left(\frac{V_{\text{switch}}}{\text{Volts}}\right)^{1/2}$$

$$E = \frac{1}{2} CV_{\text{switch}}^2 = \frac{\epsilon_0 \epsilon_r AV_{\text{switch}}^2}{L}$$

Flatte, AIP Advances 7, 055923 (2017)
VTSS: Topological surface states as leakage

Sources of dissipation:
- Charge transport in bulk
- Charge transport in surface states
- Spin recombination current at interface
- Spin diffusion current into bulk.

\[ H = \nu \left[ k_x \sigma_y - k_y \sigma_x \right] + b_z \sigma_z \]

Caveat: experimentally observed “gaps” vary by orders magnitude, 25-100 meV [ARPES], 100-200 μeV [transport].

Sanchez-Barriga et al., *Nature Comm.* 7, 10559 (2016)

Flatte, AIP Advances 7, 055923 (2017)
Breaking time-reversal symmetry in 3D TI

2D Dirac equation for massive free electrons breaks time-reversal symmetry:

\[ i\hbar \frac{\partial}{\partial t}\psi = \left[ \left( -p_x \sigma_y + p_y \sigma_x \right) c + \sigma_z mc^2 \right] \]

Similarly, on the surface of a 3D TI, breaking time reversal symmetry should create a “mass” or a gap:

\[ H = v \left[ k_x \sigma_y - k_y \sigma_x \right] + b_z \sigma_z \]

Can we detect this gap? How does it affect the properties of a topological insulator?
ARPES measurements of ferromagnetic (magnetically-doped) TI thin films suggest the formation of a gap. But this is complicated by disorder & controversial. Other mechanisms for getting a ‘non-magnetic’ gap.

Xu et al., Nature Phys. 8, 616 (2012)
Also: Yulin Chen et al., Science 329, 659 (2010)


ARPES measurements of Mn-Bi$_2$Se$_3$ vs. Zn-Bi$_2$Se$_3$
Broken time-reversal symmetry: spin textures

Xu et al., Nature Phys. 8, 616 (2012)

Surface gating of chemical potential

**Geometric Phase**

\[
\text{Geometric Phase} = \pi \left[ 1 - \frac{v k \tan \theta}{E_F} \right]
\]

- Creation of “hedgehog spin texture”
- Dosing with NO₂ allows “chemical gating” of geometric phase
Broken time-reversal symmetry: Chiral edge states

\[ \sigma_{xy} = \frac{e^2}{h}, \quad \sigma_{xx} = 0 \]

Yu \textit{et al} (Science \textbf{329}, 61, 2010): ferromagnetic order in a topological insulator transforms helical Dirac surface states into chiral edge states with quantized Hall conductance and zero longitudinal conductance at $B = 0$. This is known as a “quantum anomalous Hall insulator.”
The quantum anomalous Hall effect

Four probe measurements of the Hall effect & the longitudinal resistance in large (mm scale) samples as a function of external magnetic field and temperature.

Thin films are grown on a SrTiO₃ substrates that serves as the dielectric of a capacitor.

Back gate voltage allows tuning of the chemical potential (Fermi energy)
Fully quantized edge transport at \( B = 0 \)

Hall quantization at 4 parts in \( 10^4 \)

Minhao Liu, Wong, Richardella, Kandala, Yazdani, Samarth, Ong,


Followed by:


Kou et al., *Nature Communications*, **6**, 8474 (2015)


Precision of measurement 0.17 ppm
Dissipation free edge transport at $B = 0$

Nearly dissipation free edge transport (Minhao Liu, Wong, Richardella, Kandala, Yazdani, Samarth, N. P Ong, Science Advances 2, e1600167 (2016))

$R_{xx} \sim 3 \times 10^{-4} \frac{h}{e^2}$

Contrast with quantum Hall effect: mobility in quantum anomalous Hall effect samples is only $\sim 150 \text{ cm}^2/\text{v.s}$
Activation of edge transport across gap

\[ \sigma_{xx} = \sigma_0 \exp\left(-\frac{\Delta}{k_B T}\right) \]

Ferromagnetic ordering temperature \( T_C \approx 15 \text{ K} \).

But dissipation free transport is activated by a gap \( \Delta \approx 150-200 \text{ mK} \! \)!

Is the gap induced by breaking of time reversal symmetry? Or is it a mobility gap due to disorder?

Imaging the magnetic disorder in quantum anomalous Hall insulators

Lachman et al., Science Advances 1, e1500740 (2015) [with E. Zeldov & Andrea Young]
Topological insulators & axion electrodynamics

Topological field theory: topological insulators can be regarded as magnetoelectrics

\[ L_\theta = 2\alpha \sqrt{\frac{\varepsilon_0}{\mu_0}} \frac{\theta}{2\pi} \vec{E} \cdot \vec{B} \]

‘Axion angle’ \( \theta = \pi \) in time-reversal invariant topological insulators leads to half-quantized surface Hall conductance:

\[ \sigma_{xy} = \frac{e^2}{2h} \]

Qi, Hughes, Zhang, PRB 78, 195424 (2008)
Qi et al., Science 323, 1184 (2009)
Wu et al., Science 354, 1124 (2016)

See Armitage & Wu: arXiv:1810.0123 for recent perspective
Making an ‘axion insulator’

\[ L_\theta = 2\alpha \sqrt{\frac{\epsilon_0}{\mu_0}} \frac{\theta}{2\pi} \vec{E} \cdot \vec{B} \]

‘Axion angle’ \( \theta = \pi \) in time-reversal invariant topological insulators leads to half-quantized surface Hall conductance: \( \sigma_{xy} = e^2 / 2h \).

Observation requires:
A. All surfaces gapped from broken time-reversal symmetry with \( E_F \) in gap.
B. Topological insulator should be in 3D regime to avoid finite size effect (hybridization gap)
C. Interior of topological insulator should still obey time-reversal symmetry

See Armitage & Wu: arXiv:1810.0123 for recent review
Heterostructure for axion insulator

Cr-doped and V-doped (Bi,Sb)$_2$Te$_3$ thin films: dramatically different coercive fields. Opportunity to create novel quantum anomalous Hall insulator configurations.


See also: Mogi et al., Science Advances 3, eaao1669 (2017).
Observation of the axion insulator


Low temperature MFM proves opposite magnetization in top and bottom magnetic layers (Weida Wu)
Quantum anomalous Hall edges: useful for spintronics?

- Dissipationless charge flow without a magnetic field is potentially “useful” but…
- Can the temperature at which this effect is observed be raised to a technologically relevant range? [Mogi et al., Appl. Phys. Lett. 107, 182401 (2015)].
- What is the spin polarization of the edge states and can it be used for devices? [Zhang et al., Phys. Rev. B 93, 235315 (2016)]
Quantum anomalous Hall effect: outlook

Can we increase temperature scale for observation?
What is the spin polarization of edge states?
Effect of interactions? Going beyond $C_n = \pm 1$?
Interplay between superconductivity & quantum anomalous Hall edges?
Can we directly observe axion term through topological magnetoelectric effect?
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Spintronics

Spin-resolved transport in 3D TIs
Ando *et al.*, *Nano Lett.* 14, 6226 (2014)

Topological spintronics
Liu *et al.*, *PRB* 91, 235437 (2015)

Quantum anomalous Hall effect